US008009003B2

(12) **United States Patent**
Laboure et al.

(10) **Patent No.: US 8,009,003 B2**
(45) **Date of Patent: Aug. 30, 2011**

(54) **METHOD FOR POWERING A MAGNETIC COUPLER AND DEVICE FOR POWERING AN ELECTRIC DIPOLE**

(75) Inventors: **Eric Laboure**, Cachan (FR); **Thierry Antoine Meynard**, Beauzelle (FR); **François Forest**, St Clement de Riviere (FR)

(73) Assignees: **Centre National de la Recherche Scientifique (C.N.R.S.)**, Paris (FR); **Institut National Polytechnique de Toulouse**, Toulouse (FR); **University Montpellier 2, Sciences et Techniques**, Montpellier (FR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 263 days.

(21) Appl. No.: **12/446,035**

(22) PCT Filed: **Oct. 22, 2007**

(86) PCT No.: **PCT/FR2007/001741**
§ 371 (c)(1), (2), (4) Date: **Jun. 5, 2009**

(87) PCT Pub. No.: **WO2008/056045**
PCT Pub. Date: **May 15, 2008**

(65) **Prior Publication Data**
US 2010/0315187 A1 Dec. 16, 2010

(30) **Foreign Application Priority Data**
Oct. 20, 2006 (FR) 06 09233

(51) **Int. Cl.**
H01F 30/12 (2006.01)

(52) **U.S. Cl.** **336/12**; 336/214

(58) **Field of Classification Search** 336/12, 336/214, 215
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,790,131 A 4/1957 Einard
(Continued)

FOREIGN PATENT DOCUMENTS

WO 20060040074 4/2006

OTHER PUBLICATIONS

In Gyu Park et al:, "Modeling and analysis, of multi-interphase transformers for connecting power converters in parallel", Power Electronics Specialists Conference, 1997. PESC '97 Record., 28TH Annual IEEE St .. Louis, MO, USA Jun. 22-27, 1997, New York, NY, USA, IEEE, US, vol. 2, Jun. 22, 1997, pp. 1164-1170, XPOI0241695.

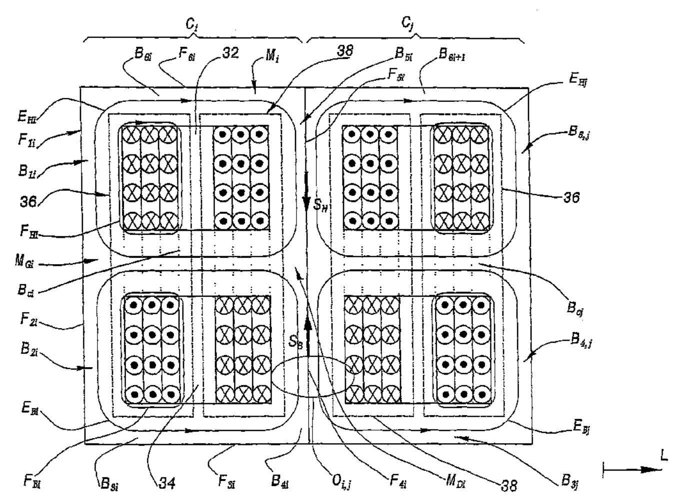
(Continued)

Primary Examiner — Anh T Mai
Assistant Examiner — Joselito Baisa
(74) *Attorney, Agent, or Firm* — Young & Thompson

(57) **ABSTRACT**

A method for powering a magnetic coupler, in which: a) each winding of a first magnetic elementary cell is powered such as to produce a magnetizing flux in a bar of the first cell which is joined with a second cell, the fundamental component of which has an angular offset x_i; and b) powering each winding of the second cell such as to produce a magnetizing flux in the bar of the second cell which is joined with the first cell, the fundamental component of which has an angular offset x_j. The absolute value of the difference between the angular offsets x_i and x_j is greater than or equal to (I) rad.

16 Claims, 14 Drawing Sheets



U.S. PATENT DOCUMENTS

3,395,373	A *	7/1968	Stephens	336/12
4,009,460	A *	2/1977	Fukui et al.	336/110
4,112,403	A	9/1978	Friedlander	
4,646,048	A *	2/1987	Hunt et al.	336/213
4,853,664	A *	8/1989	Asakura	336/12
5,003,277	A *	3/1991	Sokai et al.	336/10
5,182,535	A *	1/1993	Dhyanchand	336/12
5,416,458	A *	5/1995	Menke et al.	336/12
7,449,985	B2 *	11/2008	Urano et al.	336/178
2008/0007378	A1	1/2008	Hanser	

OTHER PUBLICATIONS

Liu Guangye et al: "Three-Phase-to-Four-Phase Transformer for Four-Phase Power-Transmission Systems" IEEE Transactions on Power Delivery, IEEE Service Center, New York, NY, US, vol. 17, No. 4, Oct. 2002, pp. 1018-1022 , XP011078870 ISSN: 0885-8977.

International Search Report dated Apr. 28, 2008, in PCT application.

* cited by examiner

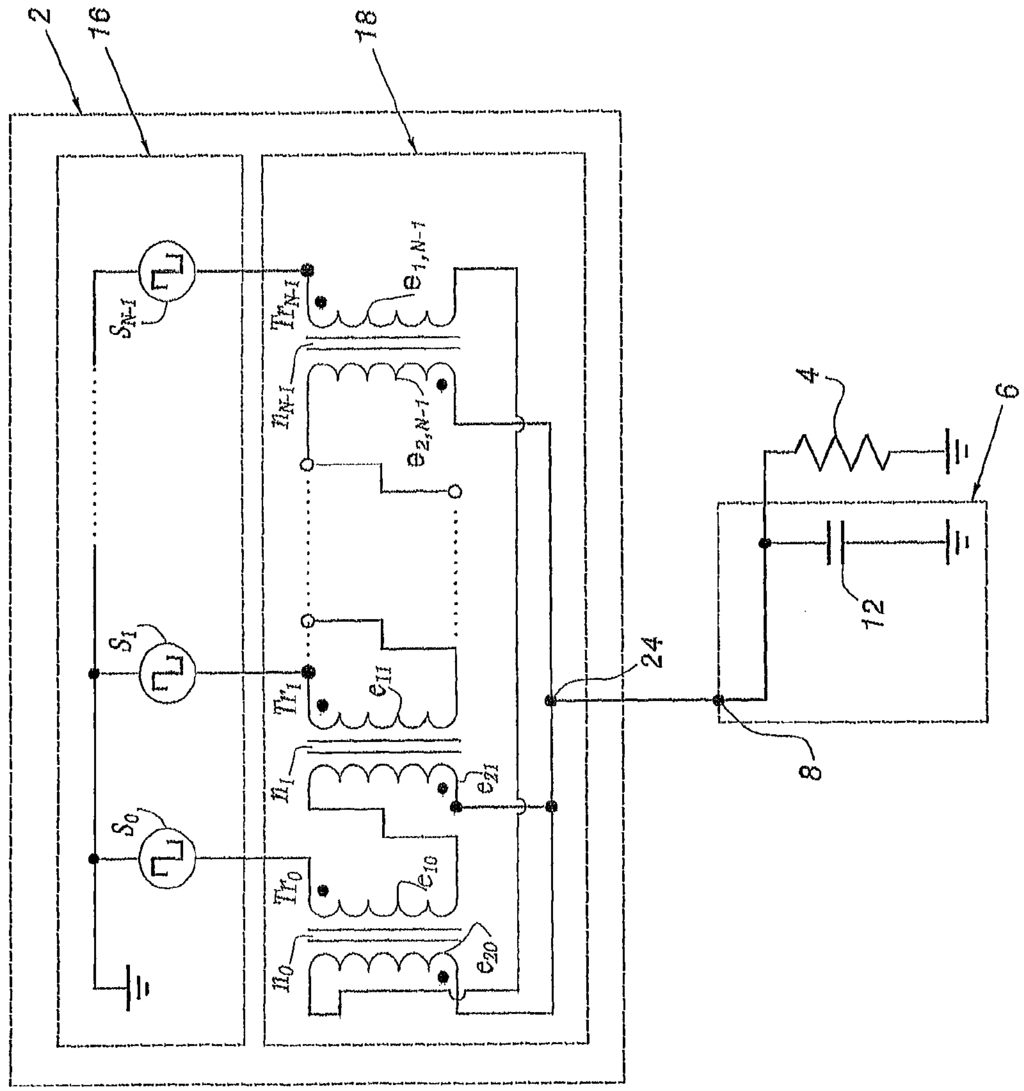

2
16
18
S_{N-1}
S_1
S_0
Tr_{N-1}
e_{1,N-1}
n_{N-1}
e_{2,N-1}
Tr_1
e_11
n_1
e_21
Tr_0
e_10
n_0
e_20
24
4
6
12
8

Fig. 1

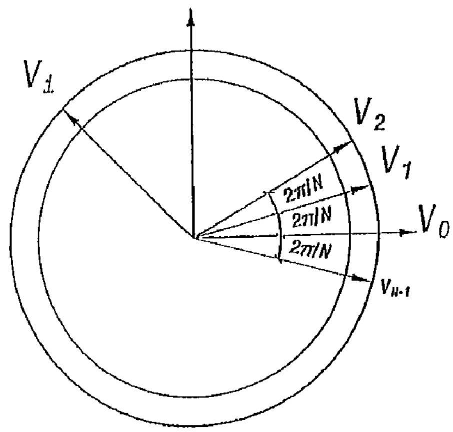


Fig. 2

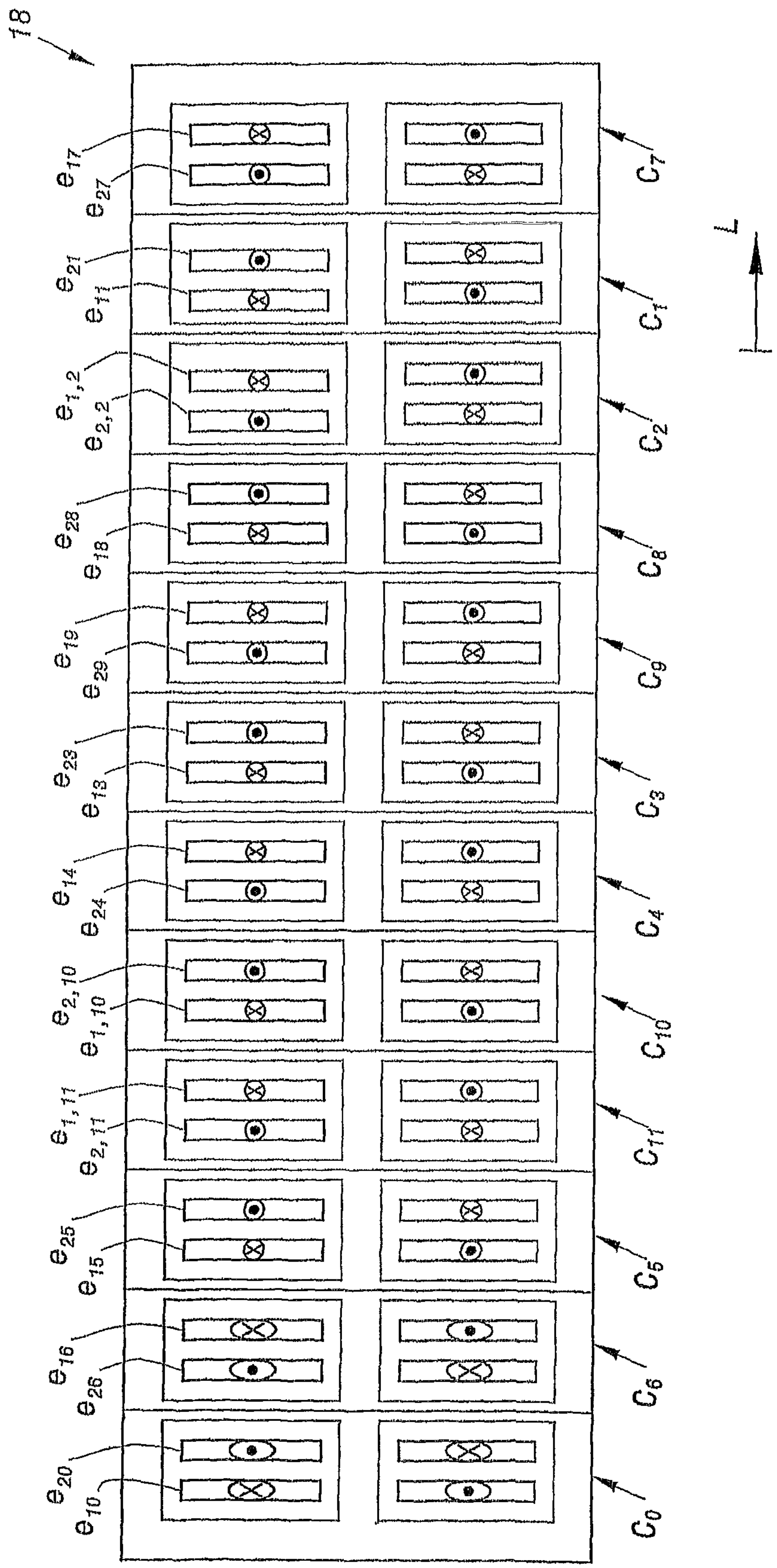

18
L
e17
e27
C7
e21
e11
C1
e1,2
e2,2
C2
e28
e18
C8
e19
e29
C9
e23
e13
C3
e14
e24
C4
e2,10
e1,10
C10
e1,11
e2,11
C11
e25
e15
C5
e16
e26
C6
e20
e10
C0

Fig.3

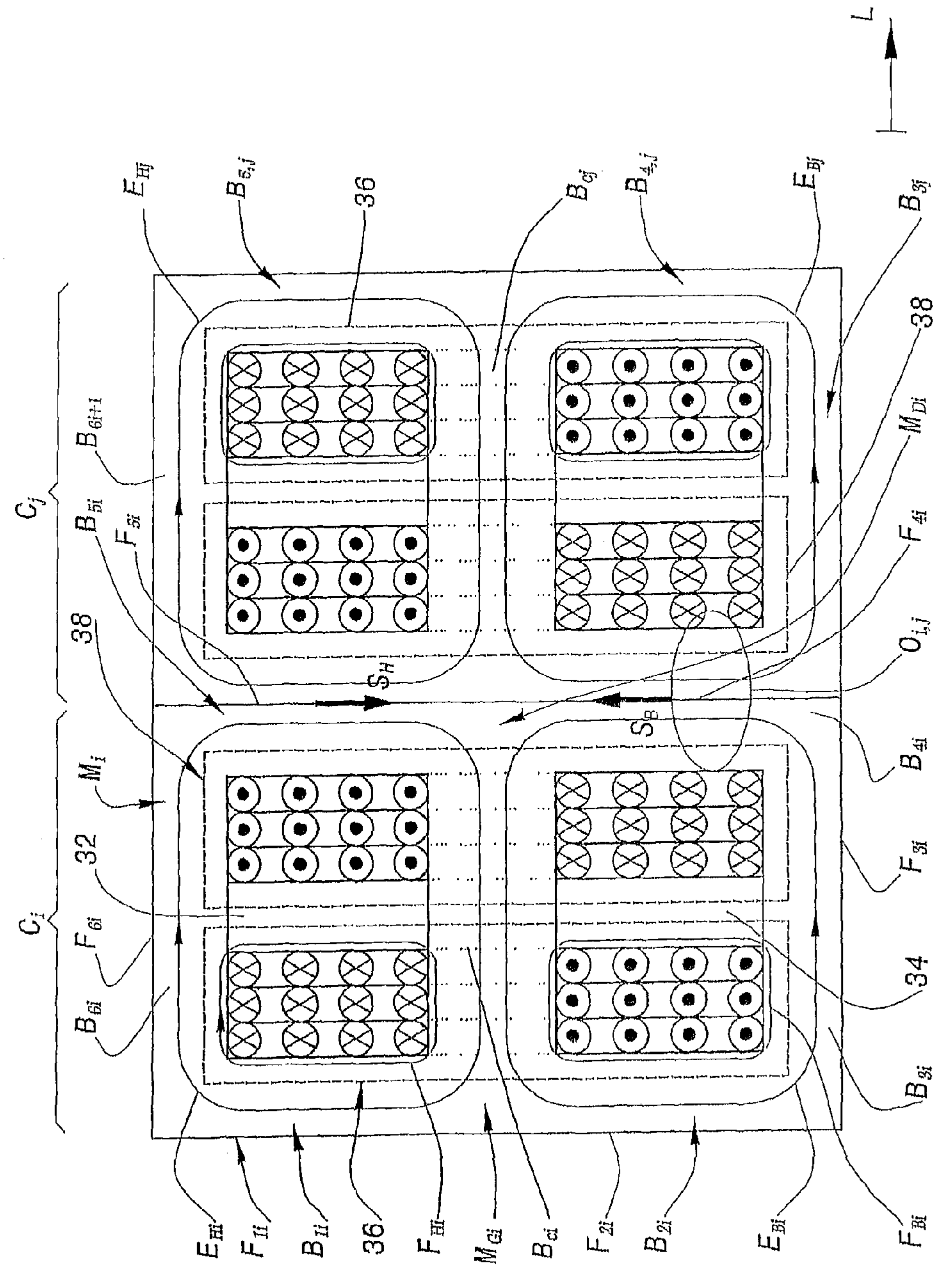


Fig. 4

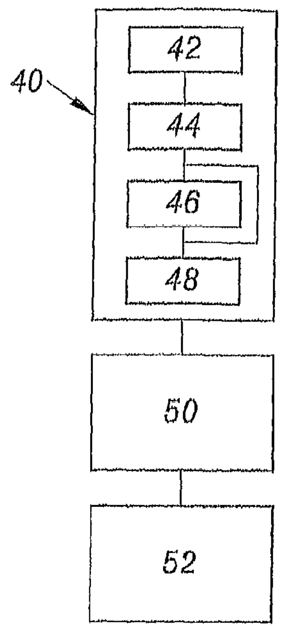


Fig.5

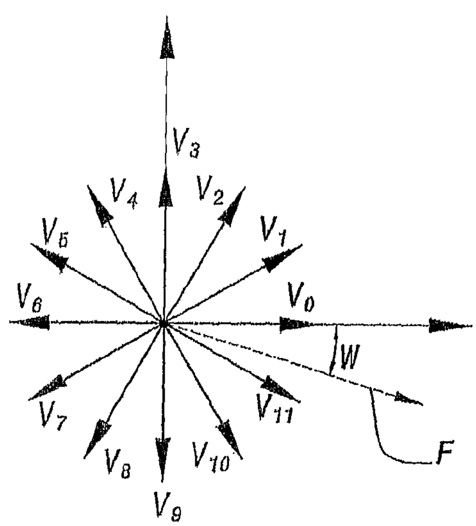


Fig.6

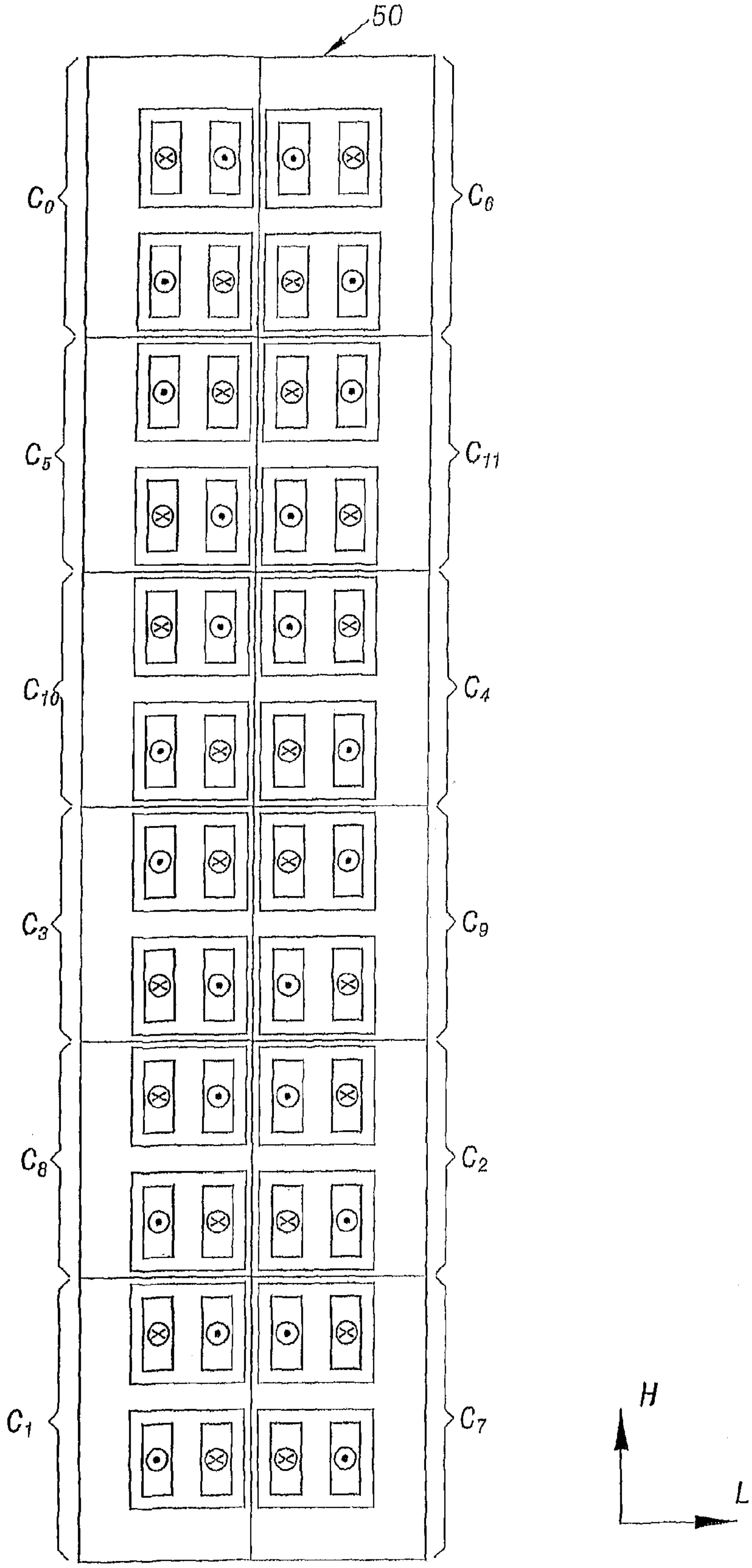


Fig. 7

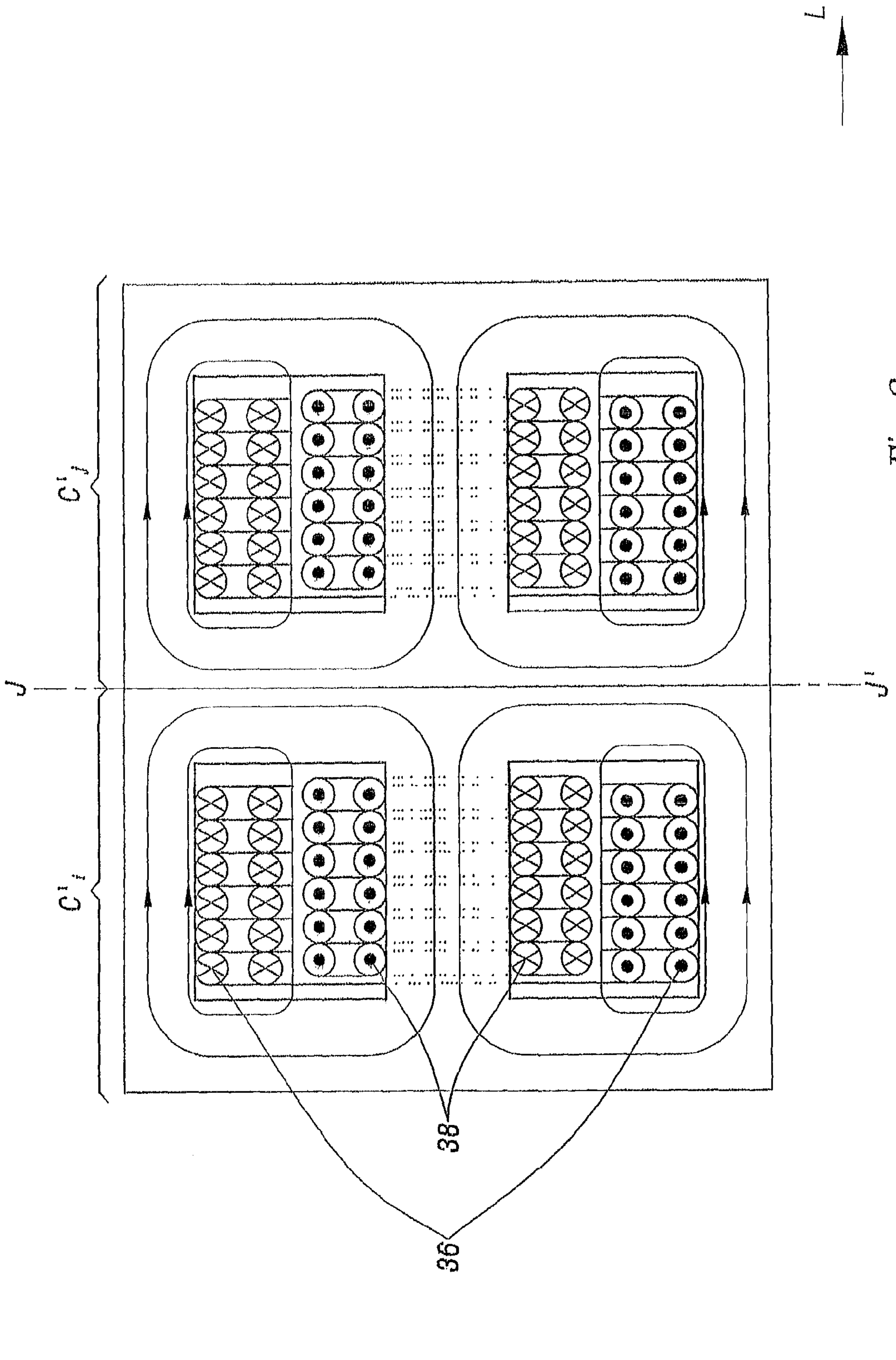


Fig.8

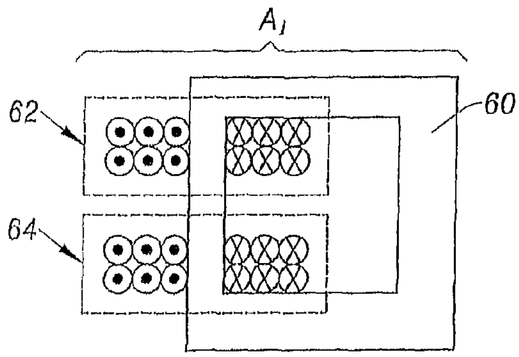


Fig.9

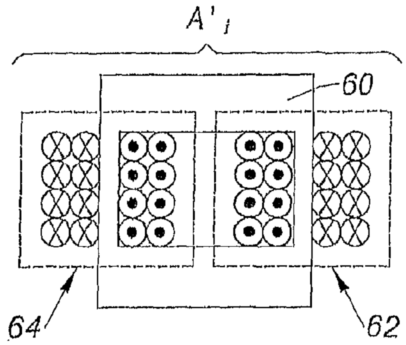


Fig.10

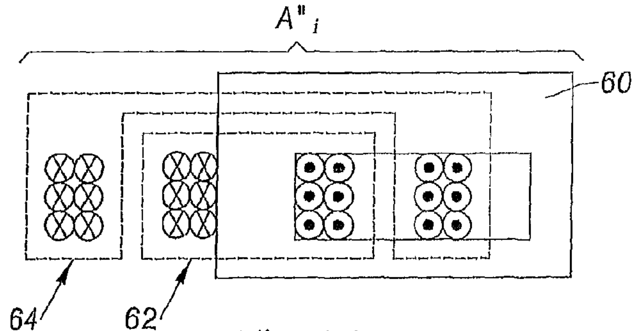


Fig.11

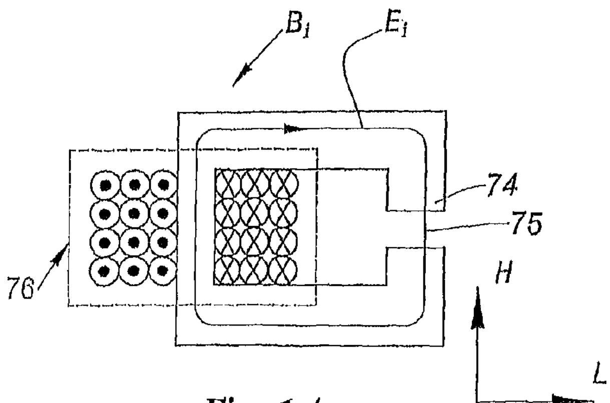


Fig.14

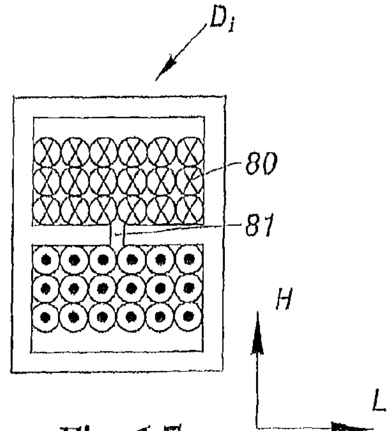


Fig.15

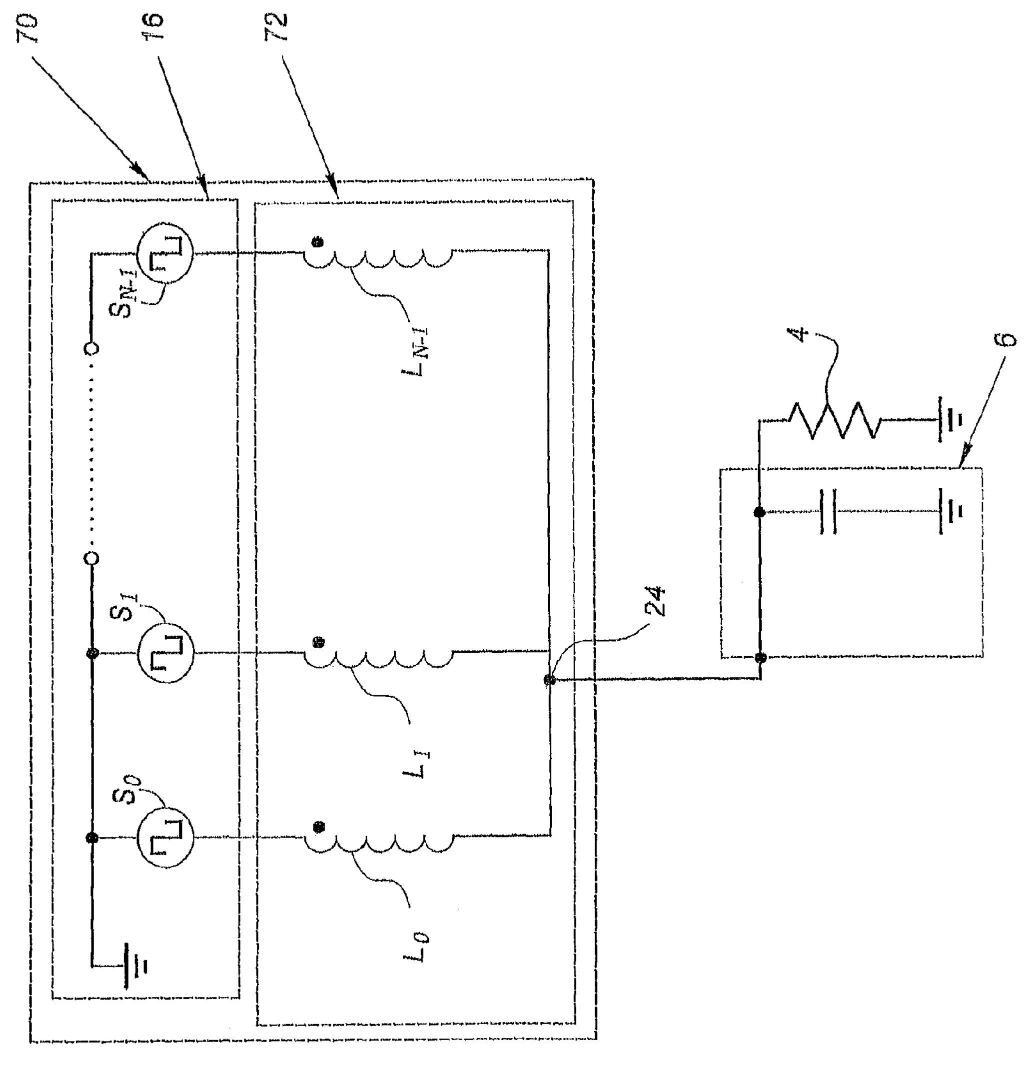


Fig. 12

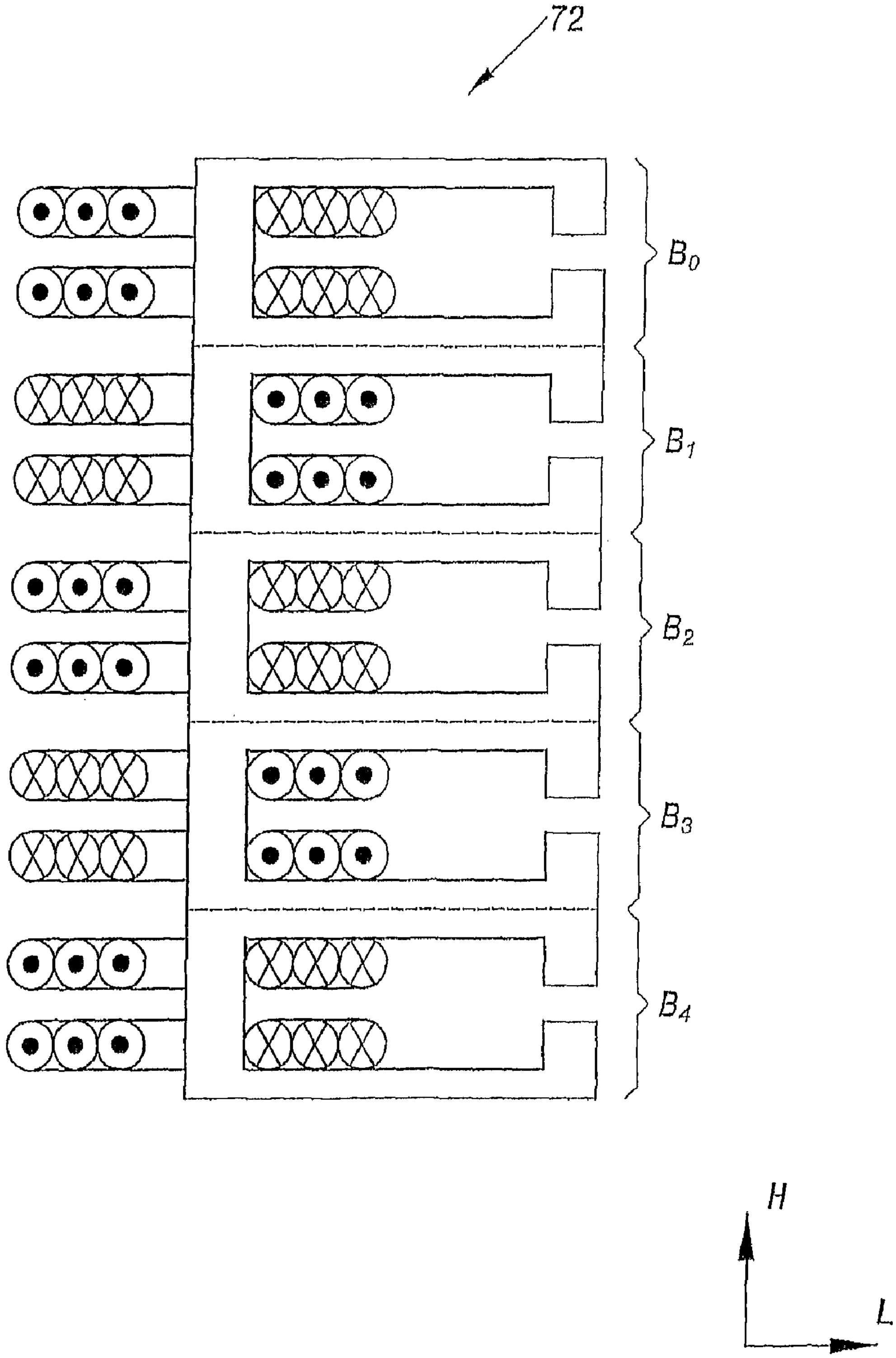


Fig. 13

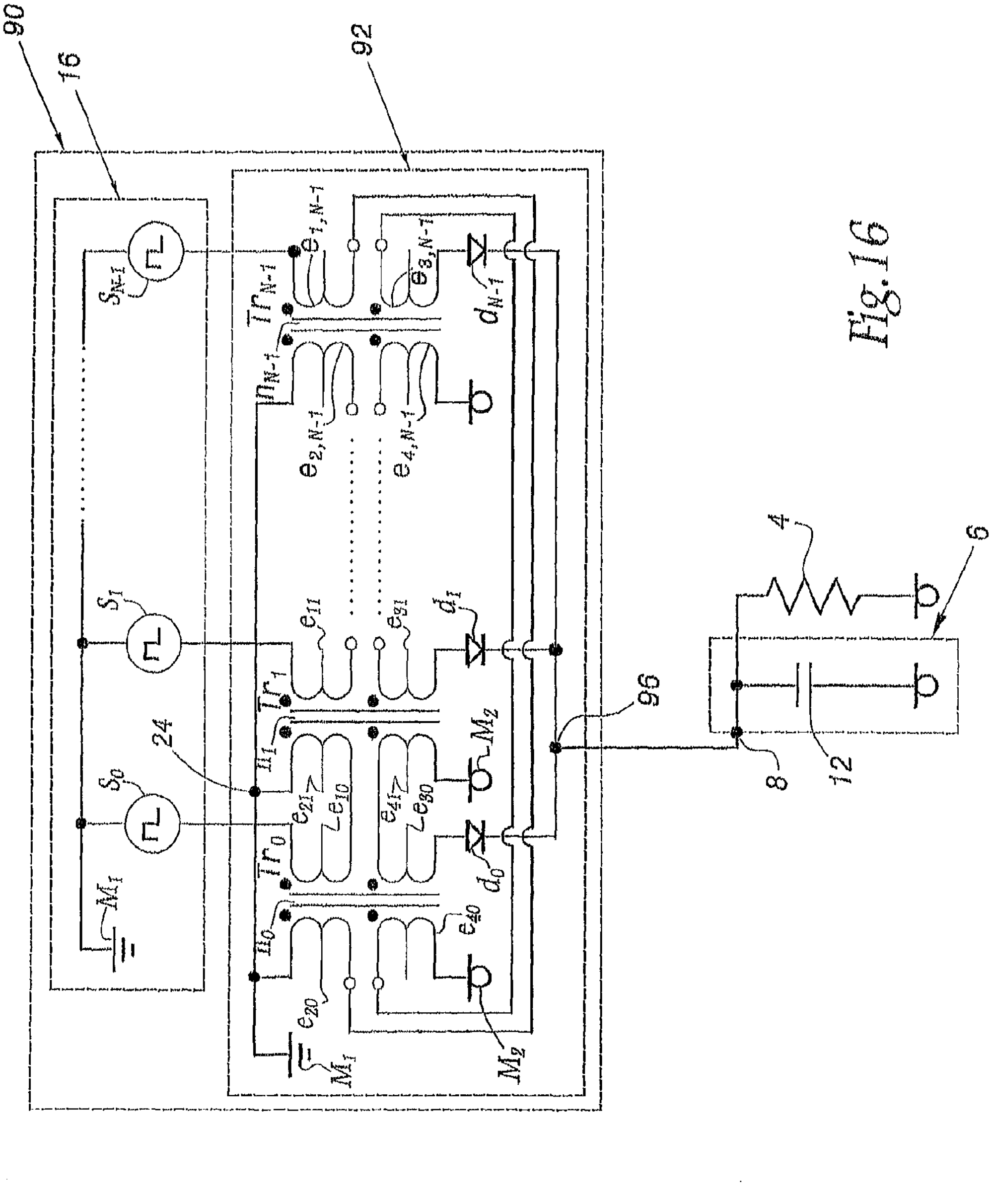

90
16
92
S_{N-1}
S_1
S_0
M_1
24
Tr_{N-1}
Tr_1
Tr_0
n_{N-1}
n_1
n_0
$e_{1,N-1}$
$e_{3,N-1}$
$e_{2,N-1}$
$e_{4,N-1}$
e_{11}
e_{31}
e_{21}
e_{10}
e_{41}
e_{30}
e_{20}
e_{40}
d_{N-1}
d_1
d_0
M_2
96
4
6
8
12

Fig. 16

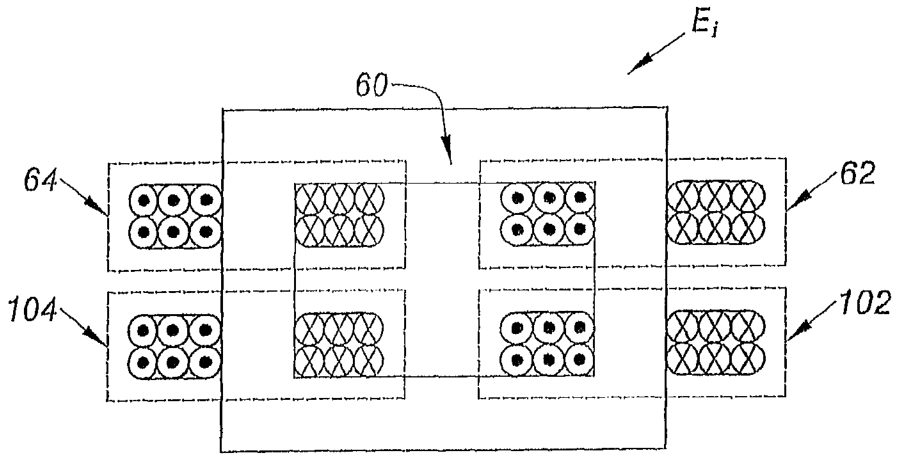


Fig. 17

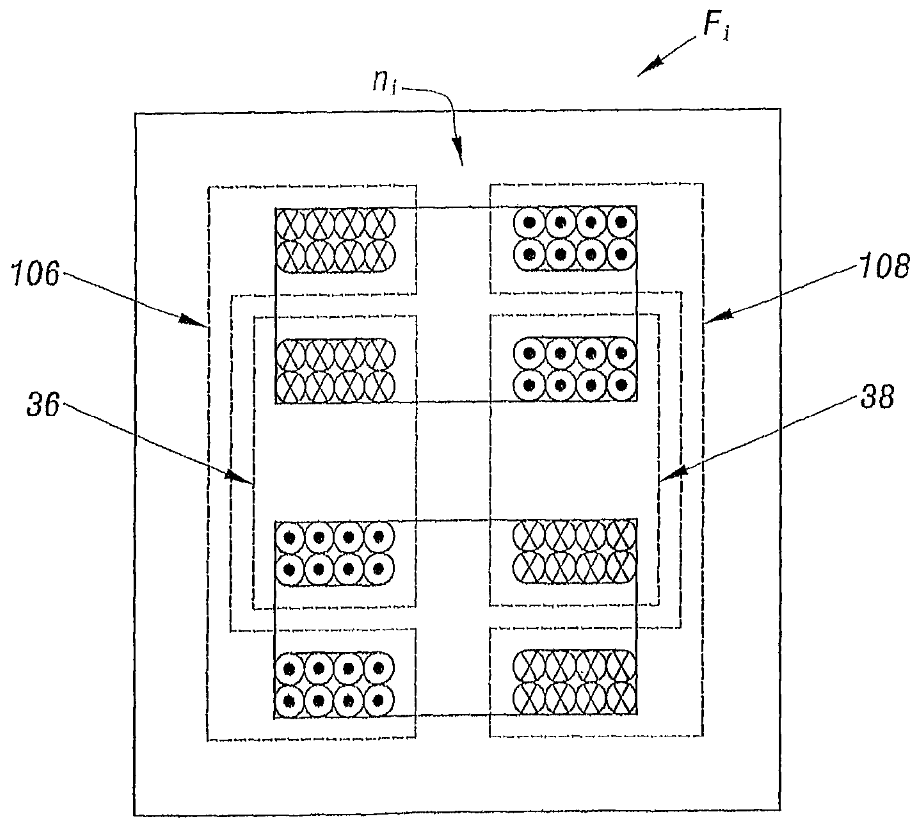


Fig. 18

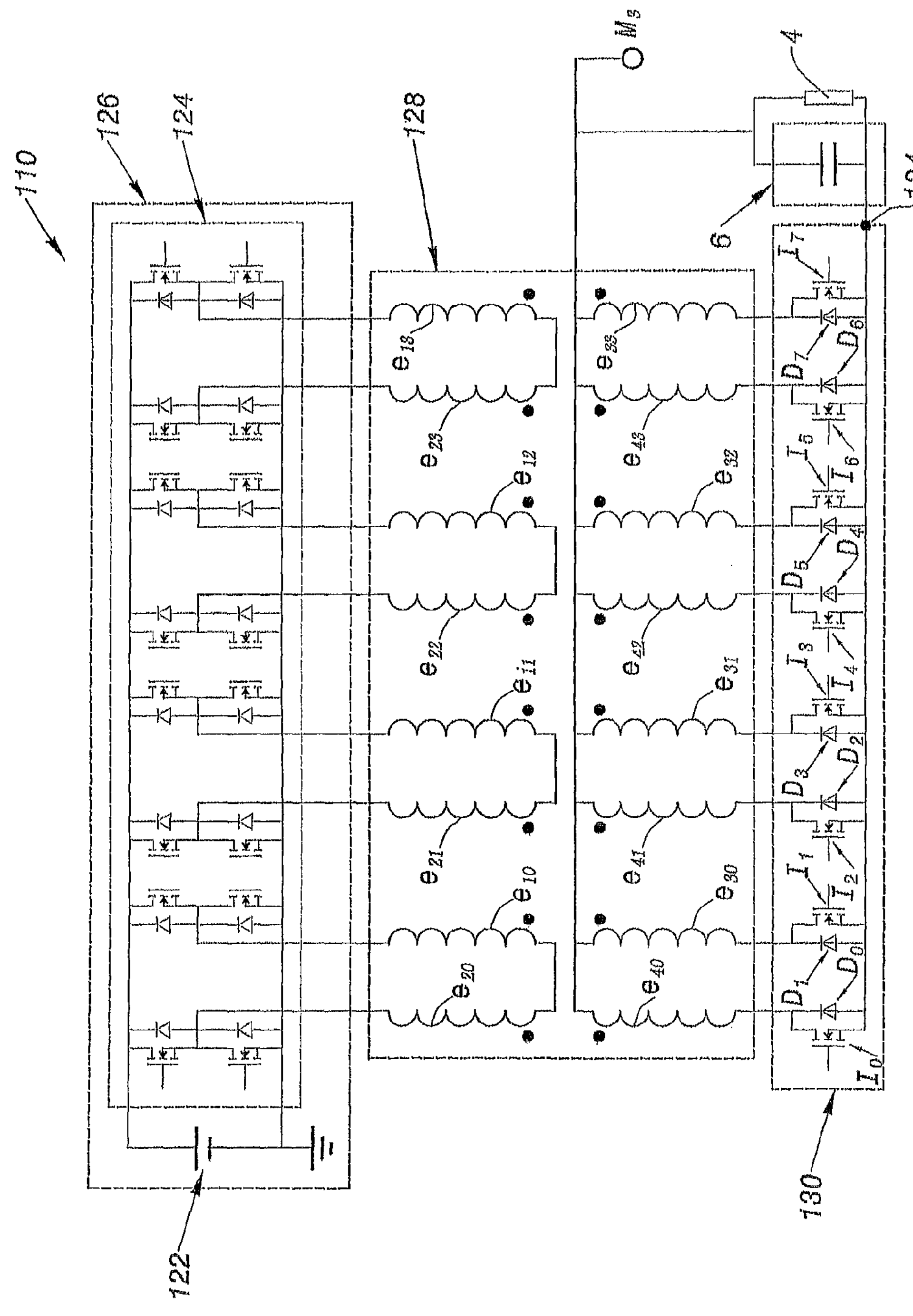

110
126
124
128
M3
4
6
134
130
122
e18
e23
e12
e22
e11
e21
e10
e20
e33
e43
e32
e42
e31
e41
e30
e40
D0
D1
D2
D3
D4
D5
D6
D7
I0
I1
I2
I3
I4
I5
I6
I7

Fig. 19

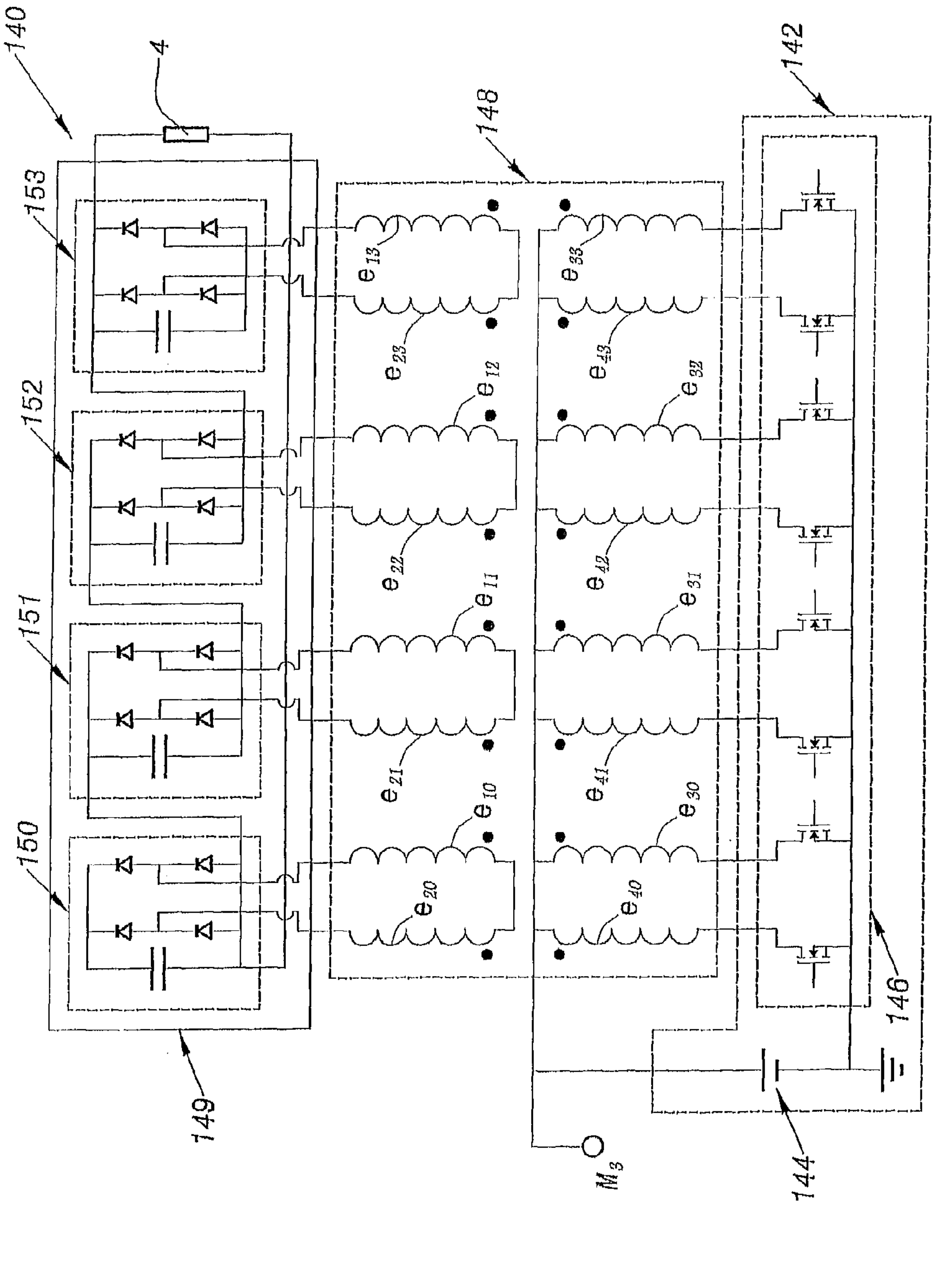

140
4
148
142
153
152
151
150
149
144
146
M_3
e_{13}
e_{23}
e_{12}
e_{22}
e_{11}
e_{21}
e_{10}
e_{20}
e_{33}
e_{43}
e_{32}
e_{42}
e_{31}
e_{41}
e_{30}
e_{40}

Fig.20

METHOD FOR POWERING A MAGNETIC COUPLER AND DEVICE FOR POWERING AN ELECTRIC DIPOLE

The present invention relates to a method and device for powering a multi-interphase transformer.

Multi-interphase transformers are used, for example, to connect a load to a multiphase power source. The following article provides further information on multi-interphase transformers: "Modelling and Analysis of Multi-Interphase Transformers for Connecting Power Converters in Parallel", IN GYU PARK and SEON IK KIM, Dept. of Control and Instrumentation Eng., Wonkwang University, Iksan, Chonbuk, 570-749 Korea, IEEE 1997.

It is known to use multiphase power sources which are capable of generating N periodic supply voltages or currents which are offset angularly from one another, N being an integer greater than or equal to four. The angular offsets between the supply voltages or currents used are distributed uniformly between 0 and 2π rad. An angular offset of 2π rad corresponds to a period of the voltage or current.

Multi-interphase transformers known to the inventors can be broken down into at least four elementary magnetic cells, each cell comprising:

- a magnetic core suitable for forming a single closed annular magnetic circuit, said core comprising for this purpose at least three non-co-linear bars forming the closed magnetic circuit, at least two of said bars having each a planar face facing the exterior of the cell, and the field lines of the closed magnetic circuit inside said bars being parallel to the planar faces,
- one or more windings, each of said windings being wound around a bar of the magnetic core so as to leave at least the two bars with a planar face free of windings, and
- the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another.

The inventors are also familiar with multi-interphase transformers which can be broken down into at least four elementary magnetic cells, each cell comprising:

- a magnetic core suitable for forming only a first and a second closed annular magnetic circuit with a common portion, said core comprising a central magnetic bar forming the common portion of the two closed magnetic circuits, and at least two non-co-linear bars each having a planar face facing towards the exterior of the cell, and the field lines of the first or second closed magnetic circuit inside said bars being parallel to the planar face thereof,
- one or more windings, each of said windings being wound around the central bar so as to leave at least the two bars with a planar face free of windings, and
- the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another.

The methods of powering these multi-interphase transformers consist of:

a) powering the or each winding of the first cell with one of the supply voltages or currents so as to produce a magnetising flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) powering the or each winding of the second cell with one of the supply voltages or currents so as to produce a magnetising flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j

The absolute value of the difference x_i-x_j is equal to

$$\frac{2\pi}{N}.$$

Multi-interphase transformers powered in this way function correctly but are bulky.

The object of the invention is therefore to propose a method of powering these multi-interphase transformers which allows the overall size of the multi-interphase transformers to be reduced while maintaining the same performance levels.

The invention therefore relates to a method of powering these multi-interphase transformers, in which the absolute value of the difference between the angular offsets x_i and x_j is greater than or equal to

$$\frac{4\pi}{N}\text{ rad.}$$

It has been found that applying an angular offset of greater than or equal to

$$\frac{4\pi}{N}\text{ rad}$$

between the angular offsets x_i and x_j reduces the maximum magnetic flux passing through the joined bars. Indeed, this brings the angular offset closer to π rad, which corresponds to an optimal reduction in the maximum magnetic flux which can be observed in the joined bars.

Since the maximum magnetic flux passing through the bars is reduced, it is also possible to reduce the dimensions of these bars in such a way that the overall size of the multi-interphase transformer is also reduced.

In addition, owing to the uniform distribution of the angular offsets of the N supply voltages or currents, the voltage or current harmonics in the load powered by this transformer are reduced.

The embodiments of this powering method may comprise one or more of the following features:

- the absolute value of the difference between the angular offsets x_i and x_j is between

$$\pi - \frac{2\pi}{N}\text{ rad and }\pi + \frac{2\pi}{N}\text{ rad}$$

  for each pair of cells;
- each winding of a cell is connected in series with at least one other winding of another cell.

The invention also relates to a first embodiment of a device for powering an electric dipole, said device comprising:

- a power source with N phases, the angular offsets between the phases being distributed uniformly between 0 and 2π rad, N being greater than or equal to four and 2π rad representing a period of the voltage or the periodic current,
- a multi-interphase transformer which can be broken down into at least four elementary magnetic cells, each cell comprising:

a magnetic core suitable for forming a single closed annular magnetic circuit, said core comprising for this purpose at least three non-co-linear bars forming the closed magnetic circuit, at least two of said bars each having a planar face facing the exterior of the cell, and the field lines of the closed magnetic circuit inside said bars being parallel to the planar faces,

one or more windings, each of said windings being wound around a bar of the magnetic core so as to leave at least the two bars with a planar face free of windings, and

the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another,

in which:

a) the or each winding of the first cell is connected to a respective phase of the power source so as to produce, during operation, a magnetising flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) the or each winding of the second cell is connected to a respective phase of the power source so as to produce, during operation, a magnetising flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j,

the absolute value of the difference between the angular offsets x_i and x_j is greater than

$$\frac{4\pi}{N}\text{ rad.}$$

The invention also relates to a second embodiment of a device for powering an electric dipole, said device comprising:

a power source with N phases, the angular offsets between the phases being distributed uniformly between 0 and 2π rad, N being greater than or equal to four and 2π rad representing a period of the voltage or the periodic current,

a multi-interphase transformer which can be broken down into at least four elementary magnetic cells, each cell comprising:

a magnetic core suitable for forming only a first and a second closed annular magnetic circuit with a common portion, said core comprising a central magnetic bar forming the common portion of the two closed magnetic circuits, and at least two non-colinear bars each having a planar face facing towards the exterior of the cell, and the field lines of the first or second closed magnetic circuit inside said bars being parallel to the planar face thereof,

one or more windings, each of said windings being wound around the central bar so as to leave at least the two bars with a planar face free of windings, and

the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another,

in which:

a) the or each winding of the first cell is connected to a respective phase of the power source so as to produce, during operation, a magnetising flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) the or each winding of the second cell is connected to a respective phase of the power source so as to produce, during operation, a magnetising flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j,

the absolute value of the difference between the angular offsets x_i and x_j is greater than

$$\frac{4\pi}{N}\text{ rad.}$$

The embodiments of these power devices may comprise one or more of the following features:

the absolute value of the difference between the angular offsets x_i and x_j is between

$$\pi-\frac{2\pi}{N}\text{ rad and }\pi+\frac{2\pi}{N}\text{ rad}$$

for each cell;

each winding of the second cell is inferred from the corresponding winding of the first cells by means of axial symmetry along an axis which is co-linear with the joined faces;

each cell comprises at least one first and one second winding wound in opposite directions around the same bar;

each cell comprises at least one first and one second winding, the first winding and the second winding being connected to respective phases of the power source in such a way that, during operation, the angular phase difference between the supply voltages of each of said windings is between

$$\pi-\frac{2\pi}{N}\text{ and }\pi+\frac{2\pi}{N}.$$

A clearer understanding of the invention will be achieved upon reading the following description which is given only by way of non-limiting examples and is described in reference to the drawings, in which:

FIG. **1** is a circuit diagram of a device for powering an electric dipole by means of a multi-interphase transformer;

FIG. **2** is a diagram which shows the distribution of the phases of a power source for the device in FIG. **1**;

FIG. **3** is a schematic diagram of a first embodiment of a multi-interphase transformer which can be used in the device in FIG. **1**;

FIG. **4** is a schematic diagram of a first and a second elementary magnetic cells which can be used in the multi-interphase transformer in FIG. **3**;

FIG. **5** is a flowchart of a method of powering the multi-interphase transformer in FIG. **3**;

FIG. **6** is a diagram showing the distribution of the phases of a power source with twelve phases,

FIG. **7** is a schematic diagram of the construction of another embodiment of a multi-interphase transformer which can be used in the device in FIG. **1**;

FIGS. **8** to **11** are schematic diagrams of different embodiments of elementary magnetic cells which can be used in the multi-interphase transformers in FIGS. **3** and **7**;

FIG. **12** is a circuit diagram of another embodiment of a device for powering an electric dipole by means of a multi-interphase transformer;

FIG. **13** is a schematic diagram of a multi-interphase transformer which can be used in the device in FIG. **12**;

FIGS. **14** and **15** are schematic diagrams of elementary magnetic cells which can be used in the multi-interphase transformer of FIG. **13**;

FIG. **16** is a circuit diagram of another embodiment of a device for powering an electric dipole by means of a multi-interphase transformer;

FIGS. **17** and **18** are schematic diagrams of different embodiments of elementary magnetic cells which can be used to form a multi-interphase transformer usable in the device in FIG. **16**;

FIGS. **19** and **20** are circuit diagrams of a DC-DC converter using the same multi-interphase transformer as that used in the device in FIG. **16**.

FIG. **1** shows a device **2** for powering an electric dipole **4**. In this case, the dipole **4** is connected to the device **2** by a filter **6** provided with an input **8**.

The dipole **4** is a resistor for example.

The filter **6** is for example a filter comprising only a filter capacitor **12** connected in parallel with the terminals of the dipole **4**. In this case, the device **2** enables a filter choke to be dispensed with.

The device **2** comprises a source **16** of multi-phase voltage and a multi-interphase transformer **18** to connect the source **16** to the dipole **4**.

The source **16** is a source with N phases, N being an integer greater than or equal to 4. The source **16** thus supplies N voltages V_i, where the reference i is the number of the phase between 0 and N−1. By convention, the angular offset between the voltages V_0 and V_i is assumed to be

$$\frac{2\pi i}{N}\text{ rad.}$$

The angular onsets between the voltages V_0 to V_{N-1} are thus uniformly distributed between 0 and 2π rad, as shown in FIG. **2**.

In FIG. **2**, each vector corresponds to a voltage Vi, the modulus of this vector corresponding to the modulus of the fundamental of the voltage and the angle of said vector to the x-axis corresponding to the angular offset thereof from the fundamental of the voltage V_0. As shown, when the angular offset of the fundamentals of the voltages V_0 to V_{N-1} is uniformly distributed, the angular phase difference between two successive voltage vectors in the diagram in FIG. **2** is equal to 2π/N.

In this case, the amplitudes of the voltages V_0 to V_{N-1} are all identical since all the voltages V_0 to V_{N-1} have the same periodic waveforms which are offset from one another by an angular offset of

$$\frac{2\pi}{N}\text{ rad.}$$

In FIG. **1**, the source **16** is shown in the form of N single-phase voltage sources S_0 to S_{N-1} supplying the voltages V_0 to V_{N-1}. For example, the angular offset of the voltage generated by each source S_i can be adjusted so as to correspond to any one of the voltages V_0 to V_{N-1}. The voltages V_0 to V_{N-1} are not generated in order by the sources S_0 to S_{N-1}, as described below.

For the purposes of simplification of FIG. **1**, only three voltage sources S_0, S_1 and S_{N-1} are shown.

The source **16** is for example a multiphase power supply network, a chopper or a multiphase voltage inverter, a controllable voltage rectifier formed from diodes and thyristors or a first stage of a flyback power supply. Said periodic voltages V_i are not necessarily sinusoidal but are rectangular or triangular, for example, and may comprise a continuous component.

In this embodiment, the multi-interphase transformer **18** comprises N single-phase transformers Tr_0 to Tr_{N-1}. Each transformer is formed by a primary winding e_{1i} and a secondary winding e_{2i} which are adjacent and magnetically coupled to one another via a magnetic core n_i, where i is the same reference as used above.

Each transformer forms a pair of windings which are magnetically coupled to one another by the magnetic core n_i.

In order to simplify the figure, only three transformers Tr_0, Tr_1 and Tr_{N-1} are shown in FIG. **1**.

One end of each primary winding e_{1i} is directly connected to the source S_i.

The secondary winding e_{2i} of each transformer Tr_i is connected to the source S_{i-1} by the primary winding $e_{1,i-1}$ of the transformer Tr_{i-1}. When i is equal to zero, the secondary winding e_{20} is connected to the source S_{N-1} by the winding $e_{1,N-1}$ of the transformer Tr_{N-1}.

The end of each secondary winding not connected to one of the sources S_i is directly connected to a common point **24** which is itself directly connected to the input **8** of the filter **6**.

The multi-interphase transformer **18** will now be described in greater detail with reference to FIGS. **3** and **4** for the specific case in which the number N of phases is twelve.

FIG. **3** is a cross-section of the multi-interphase transformer **18**. This multi-interphase transformer **18** is formed from twelve elementary magnetic cells C_0 to C_{11} joined to one another in a horizontal direction L. Each cell C_i corresponds to a single-phase transformer Tr_i.

Two adjacent cells C_i and C_j are shown in greater detail in FIG. **4**.

Each cell C_i comprises a magnetic core n_i with a cross-section in the shape of a ladder or an "8". To this end, the magnetic core is formed from six lateral bars $B_{1,i}$ to $B_{6,i}$ and a central bar $B_{c,i}$. The bars $B_{1,i}$ and $B_{2,i}$ form the left side-leg M_{Gi} of the ladder. The bars $B_{4,i}$ and $B_{5,i}$ form the right side-leg M_{Di}. The side-legs M_{Gi} and M_{Di} may be formed from a single piece.

The bar B_{ci} is a central horizontal bar whereas the bars $B_{3,i}$ and $B_{6,i}$ are horizontal bars located at the top and bottom respectively of the side-legs M_{Gi} and M_{Di}.

The cross-section of each of the side-legs or bars is substantially rectangular.

More specifically, the lateral bars $B_{1,i}$ to $B_{6,i}$ each have a planar face, $F_{1,i}$ to $F_{6,i}$ respectively, which face towards the exterior of the cell C_i.

The core n_i has two windows or apertures **32** and **34** which are located above and below the central bar B_{Ci} respectively.

The cell C_i also comprises two windings **36** and **38** which are wound around the central bar B_{Ci}. The windings **36** and **38** are wound in opposite directions. Each winding preferably comprises a plurality of turns.

The winding direction of the turns of each winding is defined by a dot surrounded by a circle and a circle containing a cross. The dot surrounded by a circle indicates that a vector exits the plane of the page, whereas a circle containing a cross indicates that this vector enters into the plane of the page.

In the following description it shall be considered that the windings wound in a clockwise direction as viewed from the right-hand side of the multi-interphase transformer **18** in FIG. **3** rotate in a positive direction. The windings wound in the opposite direction rotate in a negative direction. The two following references "V_i" and "$-V_i$" are defined accordingly.

"V_i" is the supply voltage of a winding wound in the positive direction "$-V_i$" is the supply voltage of a winding wound in the negative direction.

Each of said windings **36**, **38** corresponds to a winding e_{2i} or e_{1i} of the multi-interphase transformer **18**. For this reason, each winding of a cell bears the reference e_{1i} or e_{2i} in FIG. **3**. Furthermore, only the direction of winding of each winding has been shown in FIG. **3**.

The core n_i concentrates the field lines of the magnetic field created by the windings **36** and **38**. These field lines form a magnetising flux. In FIG. **4**, two arrows represent two field lines of the magnetising flux E_{Hi} and E_{Bi} created by the windings **36** and **38** within the core n_i. These arrows also represent the following sign convention: when the amplitude of the fundamental of the magnetising flux E_{Hi} is positive, the lines of this field E_{Hi} are considered to rotate in the positive direction if they rotate in a clockwise direction. When the amplitude of the fundamental of the magnetising flux E_{Bi} is positive, the lines of this field E_{Bi} are considered to rotate in the positive direction if they rotate in an anticlockwise direction. This sign convention applies to all of the cells C_i of the multi-interphase transformer. The reference w_i is also used to denote the angular offsets of the fundamental components of the magnetic fluxes E_{Hi} and E_{Bi} from the same reference. Using this sign convention, it is possible to indicate that the same magnetising flux can be defined as moving in the positive direction with an offset of w_i or as moving in the negative direction with an offset $w_i+\pi$.

More specifically, the field line of the flux E_{Hi} enters from the right of the central bar B_{Ci} and is closed by passing through the bar B_{6i} at the top when it rotates in a positive direction. The field line E_{Bi} also enters from the right of the bar B_{6i} and is closed by means of the bar B_{3i} at the bottom when said line rotates in the positive direction. These field lines E_{Hi} and E_{Bi} correspond to a magnetising flux created by the windings **36** and **38**.

The core n_i thus enables two closed magnetic circuits to be formed. These closed magnetic circuits have a common portion, i.e. the bar B_{ci}.

As will be explained below, the amplitude and the phase of the fundamental component of this magnetising flux is a function of the angular offsets of the supply voltages of the windings **36** and **38**.

The cell C_j can be inferred from the cell C_i on account of axial symmetry. The cell C_j is thus constructionally identical to the cell C_i with the exception that the positions of the windings **36** and **38** have been swapped in relation to the positions of the windings **36** and **38** of cell C_i.

When the windings of the cell C_j are supplied with power, field lines E_{Hi+1} and E_{Bi+1} are formed in the core **30** of the cell C_j. The same sign convention as defined for cell C_i also applies to cell C_j.

The entire magnetic field generated by the windings **36** and **38** is not concentrated within the core n_i. As shown by the arrows F_{Hi} and F_{Bi}, magnetic field leakage lines are formed around the winding **36**. These lines correspond to a magnetic leakage flux. Unlike the magnetising flux, the magnetic flux leakage lines comprise at least one portion which extends outside the core n_i. For example, in this case, the magnetic flux leakage lines pass through the windows **32**, **34** in order to close. The windows **32**, **34** are formed from air for example.

In this embodiment, the faces $F_{4,i}$, $F_{5,i}$, of the cell C_i are joined, and more specifically are respectively brought into contact with the faces $F_{2,j}$ and $F_{1,j}$ of the cell C_j. The magnetising fluxes E_{Hi}, E_{Hj} and E_{Bi}, E_{Bj} thus merge in the side-legs M_{Di} and M_{Gj}.

The side-legs M_{Di} and M_{Gj} are for example adhesively bonded or connected to one another by any means enabling close contact to be maintained between the two side-legs.

The arrows S_H and S_B define a sign convention which applies to all the magnetising fluxes circulating in the joined bars. More specifically, this common sign convention enables the angular offsets of the magnetising fluxes in each cell to be compared.

In this sign convention:

x^d_i indicates the angular offset of the magnetising fluxes E_{Hi} and E_{Bi} in the bar of the cell C_i joined to the cell C_j, and

x^g_j indicates the angular offset of the magnetising fluxes E_{Hj} and E_{Bj} in the bars joined to those of the cell C_i. These references make it possible to note that, in FIG. **4**, the offset x^d_i is equal to the offset w_i since the sign conventions used to define these offsets w_i and x_i are in the same direction. Conversely, the offset x^g_j is equal to the offset $w_j+\pi$ rad since the sign conventions used to define the offsets w_j and x^g_j are in the opposite direction.

FIG. **4** likewise shows a face $O_{i,j}$ located at the intersection of the uprights M_{Di} and M_{Gj} and perpendicular to the plane of the page. There are magnetising fluxes E_{Bi} and E_{Bj} across this face $O_{i,j}$. With an identical direction of displacement for the fluxes E_{Bi} and E_{Bj}, the greater the difference between the angular offset x_i of the fundamental of the magnetising flux E_{Bi} and the angular offset x_j of the fundamental of the magnetising flux E_{Bj} is, the lower the maximum magnetising flux across the face $O_{i,j}$ is. Also, the lower the magnetising flux across the face $O_{i,j}$ is, the more the horizontal section of the bars $B_{4,i}$ and $B_{2,j}$ can be reduced, and this reduces the overall size of the multi-interphase transformer **18**. The same explanations apply to the reduction of the overall size of the bars $B_{5,i}$ and $B_{1,j}$.

The multi-interphase transformer **18** only comprises cells coupled in pairs in the horizontal direction L, i.e. coupled to one another via the faces of the uprights thereof, as was described with reference to FIG. **4**.

The design and functionality of the device **2** will now be described with reference to FIG. **5**.

Initially, in a step **40** of designing the multi-interphase transformer **18**, elementary magnetic cells which are all identical to one another are produced. For example, at this stage each of the cells is identical to the cell C_i described with reference to FIG. **4**. Subsequently, the following rules are applied:

a) the supply voltages V_i of each winding of a cell C_i are selected such that an angular offset α_i between the supply voltages of the two windings of said cell is between

$$\pi - \frac{2\pi}{N} \text{ and } \pi + \frac{2\pi}{N} \text{ rad,}$$

and

b) each cell C_i is coupled to the adjacent cell C_j, which, before gluing, generates in the bars of the left upright B_{1j} and B_{2j} the magnetic fluxes E_{Hj} and E_{Bj}, of which the angular offset x_j is between

$$x_i + \frac{2\pi}{N} + \pi \text{ and } x_i - \frac{2\pi}{N} + \pi.$$

Rule a) corresponds to the application of the teaching of the French patent application filed as FR 05 07 136 and makes it possible to limit the overall size of the multi-interphase transformer **18** even further.

By way of example, the application of rule a) leads to the selection of the voltage pair V_i shown in the following Table for each cell:

Table 1: see annex at the end of the description.

In Table 1, the symbol C_i indicates the cell. In each column C_i, the symbols V_i on the left and right identify the corresponding voltages of the windings, on the left and right respectively, of the cell C_i.

Since the supply voltages V_i all have the same amplitude, and the angular offset α_i being the same for each of the cells C_i, the amplitude of the fundamental of the magnetising flux generated by each of the cells is thus identical. Thus, the application of rule b) consists of:

1) estimating, in an operation **42**, the angular offset w_i of the magnetising flux generated by each cell C_i from the supply voltages in Table 1, and
2) joining, in an operation **44**, each cell C_i to another cell C_j in such a way that the absolute value of the difference γ between the angular offsets x_i and x_j of the magnetising fluxes in the joined bars is between

$$\pi - \frac{2\pi}{N} \text{ and } \pi + \frac{2\pi}{N}.$$

The estimation of the angular offset w_i will now be explained using FIG. **6** in the particular case of the cell C_0.

FIG. **6** corresponds to the graph in FIG. **2** in the case where $\underline{N}$ is equal to twelve.

Based on Table 1, the voltages V_0 and V_5 are used to power the windings **36** and **38** respectively of the cell C_0.

The angular offset w_i of the magnetising flux can be estimated as the vector sum of the voltage vector $\vec{V}_0$ and the vector $-\vec{V}_5$. The result of this vector summation is shown in FIG. **6** by a dashed arrow F. This arrow F makes an angle $\underline{w}$ of

$$\frac{-\pi}{12} \text{ rad}$$

with the x-axis. This angle $\underline{w}$ corresponds to an estimate of the angular offset w_0.

It will be noted that to obtain this result it is necessary to take the inverse of the voltage vector $\vec{V}_5$, because the winding **38** is wound in the negative direction.

In the case of the multi-interphase transformer **18**, at the end of the operation **42**, Table 2 is obtained, the second line of which shows the offsets w_i:

Subsequently, during the operation **44**, the cells C_i are classified by increasing or decreasing order of angular offset w_i.

In the present case, the list of cells classified by increasing order of angular offset w_i is as follows:

$\{C_0, C_5, C_{10}, C_3, C_8, C_1, C_6, C_{11}, C_4, C_9, C_2, C_7\}$.

At this stage, in a first embodiment, the cells are joined to one another in the horizontal direction L in the increasing order shown above. Thus, the bars B_{5i} and B_{4i} of the cell C_i are joined to the bars $B_{1,j}$ and $B_{2,j}$ respectively of the following cell C_j.

In this first embodiment, it is checked that the difference γ between the angular offsets x^d_i and x^g_j is approximately π rad. For example, the angular offset w_0 is in this case equal to $-\pi/12$ whilst the angular offset w_5 is equal to $\pi/12$ rad. The offset x^d_i in the bar B_{50} is therefore equal to $-\pi/12$ rad. The offset x^g_5 in the bar B_{15} is equal to $w_5+\pi$, i.e. $\pi/12+\pi$, because in the bar B_{15}, the sign convention adopted for defining the offset of the flux E_{H5} is in the opposite direction of the arrow S_H. The difference γ is therefore equal to $\pi+2\pi/12$ rad in this case.

In the first embodiment, the offsets w_i are distributed over 360° and the continuous components of the magnetic fluxes in the joined bars do not cancel out.

To obtain a second embodiment of the multi-interphase transformer, in which the differences γ are even closer to π rad, a step **46** of permuting the supply voltages is performed.

More precisely, in step **46**, using Table 2, the cells are divided into two halves in such a way that the angular offset w_i of each cell in the first half is less than all the angular offsets w_i of the cells in the second half. For example, in this case, the second half consists of the last six cells in the classification in increasing order shown above, i.e. in this case the cells C_6, C_{11}, C_4, C_9, C_2 and C_7.

Subsequently, the supply voltage of the left winding of each of the cells in this second half is permuted with the supply voltage of the right winding of the same cell. This permutation of the supply voltages does not alter the position of the windings **36** and **38**. Thus, using the notations defined with reference to Table 1, this operation of permuting the voltages of a cell makes it possible to pass from the couple of supply voltages $(V_a, -V_b)$ to the supply couple $(V_b, -V_a)$.

In contrast, the operation of permuting the voltages reverses the direction in which the fundamental component of the magnetic flux rotates. The angular offset w_i of each permuted cell is thus incremented by π rad. The second line of Table 3 below shows the angular offset w_i of each cell C_i at the end of step **46**:

TABLE 2

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
$-\frac{\pi}{12}$	$\frac{9\pi}{12}$	$\frac{19\pi}{12}$	$\frac{5\pi}{12}$	$\frac{15\pi}{12}$	$\frac{\pi}{12}$	$\frac{11\pi}{12}$	$\frac{21\pi}{12}$	$\frac{7\pi}{12}$	$\frac{17\pi}{12}$	$\frac{3\pi}{12}$	$\frac{13\pi}{12}$

TABLE 3

C_0	C_5	C_{10}	C_3	C_8	C_1	C_6	C_{11}	C_4	C_9	C_2	C_7
$-\frac{\pi}{12}$	$\frac{\pi}{12}$	$\frac{3\pi}{12}$	$\frac{5\pi}{12}$	$\frac{7\pi}{12}$	$\frac{9\pi}{12}$	$-\frac{\pi}{12}$	$\frac{\pi}{12}$	$\frac{3\pi}{12}$	$\frac{5\pi}{12}$	$\frac{7\pi}{12}$	$\frac{9\pi}{12}$

It can thus be seen that the angular offsets of the set of cells are now distributed over 180°, and no longer over 360°.

Subsequently, still in step **46**, the cells C_i thus obtained are again classified by increasing order of angular offset w_i. The following classification is thus obtained:

$\{C_0, C_6, C_5, C_{11}, C_{10}, C_4, C_3, C_9, C_8, C_2, C_1, C_7\}$.

In this second embodiment, the cells C_i thus obtained are then joined in the horizontal direction L in the order shown above.

The first line of Table 4 (see annex) shows the order of the cells in this second embodiment. The second line shows the voltage at which each of the windings of each cell is connected.

It is checked that in the second embodiment the difference γ obtained is closer to π rad than in the first embodiment. For example, the angular offsets w_0 and w_6 of the joined cells C_0 and C_6 are both equal to $-\pi/12$ rad. Consequently, the angular offset $x^d{}_0$ in the bar B_{50} before gluing is equal to $-\pi/12$ rad. The angular offset $x^g{}_6$ in the bar B_{16} before gluing is equal to $-\pi/12+\pi$. In fact, as before, the sign convention for defining the offset w_6 is in the opposite direction from the arrow S_H. Thus, in the bar B_{16}, the offset $x^g{}_6$ is given by the following relationship: $x^g{}_6=w_6+\pi$.

The difference γ is equal to π rad.

It will also be noted that the difference γ between the joined bars of the cells C_6 and C_5 is equal to $\pi+2\pi/12$ rad.

Thus, the maximum amplitude of the fundamental of the magnetising flux in the joined uprights of a pair of cells is substantially zero. Moreover, the maximum amplitude of the magnetising flux generated within the joined uprights of two cells belonging to different pairs is greatly reduced. This makes it possible to reduce greatly the section of these uprights and therefore the overall size of the multi-interphase transformer **18**.

This second embodiment therefore makes it possible to make the difference γ even closer to π rad. However, neither the first nor the second embodiment makes it possible to cancel the continuous components of the magnetising fluxes in the joined bars.

To cancel this continuous component in the joined bars, a step **48** of permuting the positions of the coils is then performed. The step **48** is in this case applied to half of the cells. Step **48** may be performed after step **46** or straight after step **40**.

In step **48**, the first two cells of the list of cells classified by increasing order are grouped to form a first pair, then the following two cells are grouped to form a second pair, and so on.

Subsequently, for the second element of each pair, the position of the two coils of the cell is permuted relative to the position on which the classifying operation was based. For example, in the case of the cell C_6, in the operation **46**, the windings **36** and **38** are on the left and right of the cell respectively. Once the positions have been permuted, the windings **36** and **38** are on the right and left of the cell respectively.

Subsequent to a permutation of this type, the windings immediately to the right and left of a joined bar are wound in the same direction. A configuration of this type reduces or cancels the continuous components of the magnetising fluxes in the joined bars. Moreover, the permutation of the position of the windings does not alter the angular offset w_i of the cell, because the windings **36** and **38** are still supplied with the same voltages. Finally, only the position of the windings is altered. Under these conditions, step **48** makes it possible, in addition to the reduction of the maximum amplitude of the fundamental component of the magnetising flux in the joined bars, also to reduce the continuous component in said joined bars.

For example, Table 5 below shows the supply voltages, of each cell of the multi-interphase transformer, obtained at the end of steps **46** and **48**. The first line shows the order of the cells. The second line shows the supply voltages of the left and right coils of each cell.

Table 5 (See Annex)

After design, in a step **50**, the angular offset of each supply S_0 to S_{N-1} is controlled in such a way that the supply voltage of the first windings e_{1i}, e_{2i} of each cell C_i corresponds to that which was determined in the design step **40**.

Consequently, in a step **52**, the windings of each cell are powered using the source **16** controlled in this way. This makes it possible to supply the dipole **4** from a multiphase supply.

The multi-interphase transformer **18** has been described in the particular case where it is formed of twelve cells. However, what has been described above is applicable to any multi-interphase transformer formed of at least four cells. By way of example, Tables 6 and 7 below describe the configuration of multi-interphase transformers having from 4 to 20 cells obtained by performing operations **46** and **48**.

More precisely, in each of these Tables 6 and 7, column "N" shows the total number of cells and the following columns show what supply voltages are to be used for each cell C_i to power the windings thereof. In these Tables, each column C_i is divided into two sub-columns. The left and right sub-columns show the supply voltage at which the left and right windings respectively of this cell must be connected. In these sub-columns, the absolute value of the number j shown indicates that this winding must be supplied with the voltage V_{j-1}. The "–" symbol before the number j simply indicates that this winding is wound in the negative direction.

Table 6 (See Annex)

Table 7 (See Annex)

FIG. **7** shows a multi-interphase transformer **50** which can be used instead of and in the place of the multi-interphase transformer **18** in the device **2**.

This multi-interphase transformer **50** likewise comprises twelve cells C_i which are respectively identical to the cells C_i of the multi-interphase transformer **18**. In contrast to the multi-interphase transformer **18**, the cells C_i of the multi-interphase transformer **50** are joined not only in the horizontal direction L, as in the multi-interphase transformer **18**, but also in a vertical direction H.

More precisely, each pair of cells $(C_0; C_6)$; $(C_5; C_{11})$; $(C_{10}; C_4)$; $(C_3; C_9)$; $(C_8; C_2)$ and $(C_1; C_7)$ is joined in a horizontal direction via the respective vertical uprights thereof. Moreover, each pair of cells is also joined in the vertical direction H to another pair of cells via the horizontal bars thereof. The cells are joined in the vertical direction in the same way as in the horizontal direction, i.e., for example, by directly contacting the planar faces of the lateral bars of these cells. These cells may be fixed in the vertical direction by gluing or by any other means.

As in the case of the multi-interphase transformer **18**, the supply voltages of each of the windings of each cell are determined as a function of the angular offsets w_i of the magnetising fluxes.

For example, when the multi-interphase transformer **50** is designed, the procedure is the same as was described with reference to operations **42** to **48** until Table 5 is obtained. Then, alternately, for every other cell, the following operations are carried out:

permuting the supply voltages of each of the cells of these pairs, and

permuting the positions of the windings of each of these cells.

In this case, these operations are therefore applied to the following pairs of cells: $\{C_5; C_{11}\}$, $\{C_3; C_9\}$ and $\{C_1; C_7\}$.

The permutation of the supply voltages is identical to operation **46** and thus makes it possible to add an offset of π rad, allowing the fundamental component to be cancelled in the joined horizontal bars.

The step of permuting the windings is identical to operation **48** and thus makes it possible to cancel the continuous component of the magnetising flux in the joined horizontal bars.

At the end of these steps, the distribution of voltages shown in the Table below is obtained for each cell:

Table 8 (See Annex)

It is then checked that the difference γ between, for example, the offset x_5 in the bar B_{65} and the offset x_0 in the bar B_{30} is approximately π rad. In this case, w_0 and w_5 are equal to $-\pi/12$ and $\pi/12+\pi$ respectively. If the common sign convention for the bars B_{30} and B_{65} is such that the magnetising flux is positive when it is displaced from left to right in the joined bars, then $x^b_0=-\pi/12$ rad and $x^h_5=\pi/12+\pi$, where x^b_0 and x^h_5 are the angular offsets in the bars B_{30} and B_{65} respectively. Therefore the difference γ is equal to π rad.

Thus, in the multi-interphase transformer **50**, the overall size of the joined vertical uprights and of the joined horizontal bars can be greatly reduced.

FIG. **8** shows another embodiment of the cells C'_i and C'_j which can be used instead of and in the place of the cells C_i and C_j respectively.

The construction of the cell C'_i is identical to that of the cell C_i except that the winding **36** is wound around the winding **38** and not to the side. For example, the winding **36** is wound on the periphery of the winding **38**.

For example, the cell C'_j is identical to the cell C'_i.

FIGS. **9** to **11** show cells A_i, A'_i and A''_i respectively, comprising a core **60** having an annular cross-section in a vertical plane. In this case, the core **60** is formed of two horizontal bars and two vertical bars.

These cells A_i, A'_i and A''_i each comprise only two windings **62** and **64** wound in the opposite direction from one another. In the cells A_i and A''_i, the windings **62** and **64** are wound around the same bar. In the cell A_i, the winding **62** is only wound around an upper part of the vertical bar, whilst the winding **64** is only wound around a lower part of the same bar.

In the cell A''_i, the winding **64** is wound around the winding **62** and preferably around the periphery of the winding **62**.

In the cell A'_i, the winding **62** is only wound around a vertical bar of the cell, whereas the winding **64** is only wound around the other vertical bar of the cell.

The free bars of each coil of the cells A_i, A'_i and A''_i each have a planar face pointing towards the outside of the cell. These planar faces make it possible to join the cells to one another to form a multi-interphase transformer. The supply voltage of each of these windings is selected as a function of the angular offset x_i of the fundamental of the magnetising flux concentrated in the joined bars. For this purpose, the teaching provided with reference to FIG. **5** is adapted for the case involving the cells A_i, A'_i and A''_i so as to minimise the maximum amplitude of the fundamental of the magnetising flux in these bars which are joined to one another.

Finally, the cells A_i, A'_i and A''_i are basically distinguished from the cells C_i and C'_i in that in the cells A_i, A'_i and A''_i, a single annular closed magnetic circuit is established, whereas in the cells C_i and C'_i, two annular closed magnetic circuits are established on different paths.

FIG. **12** shows another supply device **70** for the electric dipole **4**. For this purpose, this device **70** comprises the power source **16** as well as a multi-interphase transformer **72** for connecting the N phases of the source **16** to the dipole **4**.

More precisely, the multi-interphase transformer **72** comprises N windings L_i producing inductance. Only one side of each winding L_i is connected to the source S_i, the other side being connected to the common point **24**.

The construction of the multi-interphase transformer **72** is described in greater detail with reference to FIG. **13** in the particular case where the number N of phases is equal to five.

The multi-interphase transformer **72** is produced by joining five identical elementary magnetic cells B_0 to B_4 in the vertical direction H. The cell B_i is described in greater detail with reference to FIG. **14**.

In this example, the cell B_i comprises a magnetic core **74** having an anular cross-section. This core **74** is formed of only two vertical bars and two horizontal bars. In this case, the three bars without coils each have a planar face pointing towards the outside and allowing this cell to be magnetically coupled to another cell. At least one of the bars comprises a gap **75** for preventing saturation of the core **74** caused by a continuous component of the magnetising flux.

The cell B_i likewise comprises only a single winding **76**, wound around only one of the vertical bars. This winding **76** generates a magnetising flux E_i concentrated in the interior of the core **74**. A single field line of the magnetising flux E_i is shown in FIG. **14**. This magnetising flux has an angular offset w_i which is a function of the angular offset of the supply voltage of the winding **76**. More precisely, in the case of the cell B_i, the estimate of the angular offset w_i is set equal to the angular offset of the supply voltage of the winding **76**.

In FIG. **13**, the cells B_i are joined to one another so as to be juxtaposed edge to edge with the planar faces of the respective horizontal bars thereof.

As before, the angular offset of the supply voltage of the windings of the cell B_i is determined in such a way as to minimise the amplitude of the fundamental of the magnetising flux circulating in the joined bars. More precisely, the supply voltages of joined cells B_i and B_j are selected in such a way that the difference between the angular offsets x_i and x_j of the fundamentals of the magnetising fluxes generated by each of these cells is as close as possible to π rad.

The method described with reference to the procedure of FIG. **5** is adapted to produce the multi-interphase transformer **72**. For example, in FIG. **13**, the windings of the cells B_1 to B_4 are all wound in the same direction. Thus, in this configuration, the windings of the cells B_0 to B_4 are supplied with the voltages V_1, V_3, V_5, V_2, and V_4 respectively.

FIG. **15** shows the architecture of a cell D_i having a core identical to the core n_i of the cell C_i. The cell D_i is only provided with a single winding **80** wound around the central bar. The central bar comprises a gap **81** for avoiding the saturation of the core n_i caused by a continuous component of the magnetising flux. This cell D_i can be used instead of and in the place of the cell B_i in multi-interface transformers similar to the multi-interphase transformer **72**.

FIG. **16** shows a third embodiment of a device **90** for supplying the dipole **4**. In this figure, the elements already described with reference to FIG. **1** have the same reference numerals, and only the differences from the device **2** are discussed here.

In FIG. **16**, the filter **6** does not have to exhibit any inductance.

The device **90** comprises the power source **16** connected to the dipole **4** via a multi-interface transformer **92**.

In the multi-interphase transformer **92**, the central point **24** is connected to a reference potential M_1 and no longer to the input **8** of the filter **6**.

In this embodiment, each transformer Tr_i comprises, in addition to the pair of windings e_{1i} and e_{2i}, a pair of windings e_{3i} and e_{4i}. The windings e_{3i} and e_{4i} are magnetically coupled to the windings e_{1i} and e_{2i} via the magnetic core n_i. The pair of windings e_{3i} and e_{4i} is electrically insulated from the windings e_{1i} and e_{2i}.

One end of the winding e_{3i} is connected via a diode d_i to a common point **96**. The cathode of the diode d_i is directed towards the common point **96**.

The common point **96** is directly connected to the input **8** of the filter **6**.

The other end of the winding e_{3i} is directly connected to one end of the winding $e_{4,i+1}$ of the following transformer Tr_{i+1}. The end of the winding $e_{4,i+1}$ which is not connected to the winding e_{3i} is connected to a reference potential M_2 electrically insulated from the potential M_1.

The end of the winding $e_{3,N-1}$ which is not connected to the common point **96** is directly connected to one end of the winding e_{40}.

The design and supply procedure for the multi-interphase transformer **92** is the same as that described with reference to FIG. **5**, so as to reduce the overall size of said multi-interphase transformer. In particular, the estimate of the angular offset w_i of a cell is obtained, using only the supply voltages of the windings e_{1i} and e_{2i}. In order to return to the previous case of two windings per cell, it is possible to equate the parts of the windings e_{1i}, e_{3i} and e_{2i}, e_{4i} respectively to the windings e_{1i} and e_{2i} of FIG. **1**.

FIG. **17** shows an example of cells E_i which can be used to form the multi-interphase transformer **92**. This cell E_i is identical to the cell A'_i except that the windings **62** and **64** have been doubled up. In FIG. **17**, the doubles of the windings **62** and **64** have the reference numerals **102** and **104** respectively.

The windings **102** and **104** are wound around the core **60** in the same direction as the windings **62** and **64** respectively. These windings **102** and **104** are electrically insulated from the windings **62** and **64** and magnetically coupled to these windings via the core **60**. The windings **62** and **64** correspond to the windings e_{1i} and e_{2i} respectively of FIG. **16** and the windings **102** and **104** correspond to the windings e_{3i} and e_{4i} respectively of FIG. **16**.

FIG. **18** shows the construction of a cell F_i which can likewise be used to produce the multi-interphase transformer **92**.

This cell F_i is identical to the cell C_i except that the windings **36** and **38** have been doubled up. The doubles of the windings **36** and **38** have the reference numerals **106** and **108** respectively. In this embodiment, the winding **106** is only wound around the winding **36** and the winding **108** is only wound around the winding **38**. The windings **106** and **108** are electrically insulated from the windings **36** and **38** and magnetically coupled to these windings **36** and **38** via the core n_i.

FIG. **19** shows the architecture of a DC-DC converter using a multi-interphase transformer as described with reference to the previous figures.

The converter **110** comprises a continuous power source **122** connected to the input of an inverter **124** which converts the continuous voltage provided by the source **122** into $\overline{N}$ periodic tensions which are angularly offset from one another by

$$\frac{2\pi}{N} \text{ rad.}$$

The inverter **124** is in this case a bidirectional current inverter. This inverter is known and the construction thereof will not be described in detail here.

The connection of the source **122** and the inverter **124** thus forms a multiphase power source **126**. The source **126** is connected to a multi-interphase transformer **128** with galvanic insulation similar to that of the multi-interphase transformer **92**. However, in this embodiment, one end of each winding e_{1i} and e_{2i} is connected directly to a respective phase of the source **126**. The other ends of each of these windings e_{1i} and e_{2i} are electrically interconnected.

One end of each of the windings e_{3i} and e_{4i} is connected to a respective input of a voltage rectifier **130**. The other end of these windings e_{3i} and e_{4i} is connected to a reference potential M_3.

The rectifier **130** comprises the same number of branches and of inputs receiving the voltage supplied by the winding e_{3i} and e_{4i}. Each branch is formed of a controlable switch I_i and a diode D_i connected in parallel. The controlable switch I_i is a switch which only allows current to circulate in one direction from the input which is connected to the winding e_{3i} or e_{4i} to a common point **134**. The different controlable switches of the rectifier **130** are controlled in such a way as to rectify the voltage supplied by each of the windings e_{3i} and e_{4i}. In this embodiment, the dipole **4** is connected between the common point **134** and the reference potential M_3.

The rectifier **130** is in this case a bidirectional current rectifier.

FIG. **20** shows another embodiment of a DC-DC converter **140**. This converter **140** comprises a multiphase power source **142** made up of a continuous voltage source **144** connected to the input of an inverter **146**. In this case, for example, the inverter **146** has unidirectional current. Each output of the inverter **146** is connected to a respective winding of a multi-interphase transformer **148**. The multi-interphase transformer **148** is identical to the multi-interphase transformer **128** except that in the multi-interphase transformer **128**, it is the ends of the windings e_{3i} and e_{4i} that are connected to the respective phases of the source **142**. For this reason, during the operation of estimating the angular offset x_i of each of the cells, the windings e_{3i} and e_{4i} as well as the supply voltages thereof are to be taken into account.

In this case, the outputs of the multi-interphase transformer **148** are connected to a voltage rectifier/step-up transformer **149**. For example, the voltage rectifier/step-up transformer **149** may be formed of a plurality of step-up transformer stages **150** to **153**. Each step-up transformer stage receives the voltages generated by a pair of coils e_{1i}, and e_{2i} respectively in order to step up a volage received at the input. A rectifier/step-up transformer of this type is known and therefore will not be described in greater detail. The load **4** is connected to the output of this rectifier/step-up transformer **149**.

Many other embodiments are possible. Here, each multi-interphase transformer has been described in the case where it is produced by gluing or fixing a plurality of elementary magnetic cells to one another. In a variant, the multi-interphase transformer has exactly the same construction as that described here, but is produced by joining a succession of magnetic cores behind one another in an E-shape. More precisely, the free ends of the horizontal bars of the E-shaped portion are joined to the vertical rear face of the following E-shaped core. The free ends of the horizontal bars of the last E-shaped core in the stack are magnetically connected via a vertical I-shaped bar. The construction of the multi-interphase transformer thus obtained is identical to that obtained by joining cells such as the cells C_i, for example. Thus, a multi-interphase transformer of this type can be broken down into elementary cells identical to those described here. From this point, it is possible to locate, within this multi-interphase transformer, portions of the core corresponding to each of the bars B_{ij}. However, in this case, the joined bars B_{ij} and B_{ij+1} come from the same material as one another, i.e. are formed in a single block. The teaching described previously can therefore be applied to a multi-interphase transformer of this type to determine what phase of the power source each winding must be connected to in order to minimise the maximum magnetic flux in the joined bars.

It is also possible to produce a multi-interphase transformer, having one of the constructions described here, from a core in a single block in which the number of openings provided is the same as the number of windows **32**, **34** required. In this last embodiment, no gluing between different cells is required. However, a multi-interphase transformer of this type can nevertheless still be broken down into elementary cells of the type described here. Thus, the teaching provided in this description can be applied to this embodiment to determine what phases of the voltage source each of the windings must be connected to in order to minimise the maximum magnetic flux in the joined bars.

A multi-interphase transformer with reduced overall size may also be produced by joining a plurality of cells in the vertical direction alone.

In this case, the multi-interphase transformer comprises the same number of windings e_{1i} and e_{2i} and phases of the power source. In a variant, each winding e_{1i} and e_{2i} is divided into a plurality of windings e_{1ik} and e_{2ik} respectively which are connected in series. Each winding e_{1ik} and e_{2ik} is subsequently used in a different cell. However, the number of windings e_{1ik} and e_{2ik} connected in series preferably remains less than $\underline{N}$.

The embodiments of the multi-interphase transformers described here are based on the particular case where the teaching of the patent application FR 05 07 136 is used within each cell in such a way as to reduce even further the overall size of each of these cells (rule a) as described with reference to FIG. **5**). However, in a variant, only rule b) as described with reference to the same figure is used to reduce the overall size of the multi-interphase transformer.

If a cell comprises two windings, the turns of these windings may be interlaced. This decreases the alternative resistance of the windings.

The planar face of the joined bars may comprise roughnesses or irregularites making it easier to couple and fix the cells to one another.

The bars around which coils are wound are not necessarily straight but may be curved.

Finally, it is also possible to use different types of cells in a single multi-interphase transformer.

The different embodiments described here have the following advantages:

- the application of rule b) for each joined bar makes it possible to reduce very distinctly the overall size and losses of the multi-interphase transformer,
- selecting the supply voltages of the windings in such a way that the difference between the angular offsets x_i and x_j of the magnetising fluxes generated by two joined cells is between

$$\pi - \frac{2\pi}{N} \text{ and } \pi + \frac{2\pi}{N} \text{ rad}$$

  makes it possible to maximise the decrease in the overall size of the multi-interphase transformer,
- dividing each winding e_{1i} connected to a phase of the power source into a plurality of windings e_{1ik} connected in series makes it possible to reduce the number of windings available to create cells, and thus to improve the possibility of approximation to an optimal configuration in which the difference in angular offsets x_i-x_j is equal to or very close to π rad.

Annex

TABLE 1

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
V_0 $-V_5$	V_5 $-V_{10}$	V_{10} $-V_3$	V_3 $-V_8$	V_8 $-V_1$	V_1 $-V_6$	V_6 $-V_{11}$	V_{11} $-V_4$	V_4 $-V_9$	V_9 $-V_2$	V_2 $-V_7$	V_7 $-V_0$

TABLE 4

C_0	C_6	C_5	C_{11}	C_{10}	C_4	C_3	C_9	C_8	C_2	C_1	C_7
V_0 $-V_5$	V_{11} $-V_6$	V_1 $-V_6$	V_0 $-V_7$	V_2 $-V_7$	V_1 $-V_8$	V_3 $-V_8$	V_2 $-V_9$	V_4 $-V_9$	V_3 $-V_{10}$	V_5 $-V_{10}$	V_4 $-V_{11}$

TABLE 5

C_0	C_6	C_5	C_{11}	C_{10}	C_4	C_3	C_9	C_8	C_2	C_1	C_7
V_0 $-V_5$	$-V_6$ V_{11}	V_1 $-V_6$	$-V_7$ V_0	V_2 $-V_7$	$-V_8$ V_1	V_3 $-V_8$	$-V_9$ V_2	V_4 $-V_9$	$-V_{10}$ V_3	V_5 $-V_{10}$	$-V_{11}$ V_4

TABLE 6

Number of cells a multiple of 4

N	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
4	1 −2	−3 4	2 −3	−4 1						
8	1 −4	−5 8	2 −5	−6 1	3 −6	−7 2	4 −7	−8 3		
12	1 −6	−7 12	2 −7	−8 1	3 −8	−9 2	4 −9	−10 3	5 −10	−11 4
16	1 −8	−9 16	2 −9	−10 1	3 −10	−11 2	4 −11	−12 3	5 −12	−13 4
20	1 −10	−11 20	2 −11	−12 1	3 −12	−13 2	4 −13	−14 3	5 −14	−15 4
N	**C_{10}**	**C_{11}**	**C_{12}**	**C_{13}**	**C_{14}**	**C_{15}**	**C_{16}**	**C_{17}**	**C_{18}**	**C_{19}**
4										
8										
12	6 −11	−12 5								
16	6 −13	−14 5	7 −14	−15 6	8 −15	−16 7				
20	6 −15	−16 5	7 −16	−17 6	8 −17	−18 7	9 −18	−19 8	10 −19	−20 9

TABLE 7

Odd number of cells

N	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
5	1 −3	−3 5	5 −2	−2 4	4 −1					
7	1 −4	−4 7	7 −3	−3 6	6 −2	−2 5	5 −1			
9	1 −5	−5 9	9 −4	−4 8	8 −3	−3 7	7 −2	−2 6	6 −1	
11	1 −6	−6 11	11 −5	−5 10	10 −4	−4 9	9 −3	−3 8	8 −2	−2 7
13	1 −7	−7 13	13 −6	−6 12	12 −5	−5 11	11 −4	−4 10	10 −3	−3 9
15	1 −8	−8 15	15 −7	−7 14	14 −6	−6 13	13 −5	−5 12	12 −4	−4 11
17	1 −9	−9 17	17 −8	−8 16	16 −7	−7 15	15 −6	−6 14	14 −5	−5 13
19	1 −10	−10 19	19 −9	−9 18	18 −8	−8 17	17 −7	−7 16	16 −6	−6 15
N	**C_{10}**	**C_{11}**	**C_{12}**	**C_{13}**	**C_{14}**	**C_{15}**	**C_{16}**	**C_{17}**	**C_{18}**	
5										
7										
9										
11	7 −1									
13	9 −2	−2 8	8 −1							
15	11 −3	−3 10	10 −2	−2 9	9 −1					
17	13 −4	−4 12	12 −3	−3 11	11 −2	−2 10	10 −1			
19	15 −5	−5 14	14 −4	−4 13	13 −3	−3 12	12 −2	−2 11	11 −1	

TABLE 8

C_0	C_6	C_5	C_{11}	C_{10}	C_4	C_3	C_9	C_8	C_2	C_1	C_7
V_0 $-V_5$	$-V_6$ V_{11}	$-V_1$ V_6	V_7 $-V_0$	V_2 $-V_7$	$-V_8$ V_1	$-V_3$ V_8	V_9 $-V_2$	V_4 $-V_9$	$-V_{10}$ V_3	$-V_5$ V_{10}	V_{11} $-V_4$

The invention claimed is:

1. Device for powering an electric dipole, comprising:

a power source with N phases, the angular offsets between the phases being distributed uniformly between 0 and 2π rad, N being greater than or equal to four and 2π rad representing a period of the voltage or the periodic current,

a multi-interphase transformer which can be broken down into at least four elementary magnetic cells, each cell comprising:

a magnetic core suitable for forming a single closed annular magnetic circuit, said core comprising for this purpose at least three non-co-linear bars forming the closed magnetic circuit, at least two of said bars each having a planar face facing the exterior of the cell, and the field lines of the closed magnetic circuit inside said bars being parallel to the planar faces,

one or more windings, each of said windings being wound around a bar of the magnetic core so as to leave at least the two bars with a planar face free of windings, and

the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another,

in which:

a) the or each winding of the first cell is connected to a respective phase of the power source so as to produce, during operation, a magnetizing flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) the or each winding of the second cell is connected to a respective phase of the power source so as to produce, during operation, a magnetizing flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j,

characterized in that the absolute value of the difference between the angular offsets x_i and x_j is greater than

$$\frac{4\pi}{N} \text{ rad.}$$

2. Device according claim **1**, wherein the absolute value of the difference between the angular offsets x_i and x_j is between

$$\pi - \frac{2\pi}{N} \text{ rad and } \pi + \frac{2\pi}{N} \text{ rad}$$

for each cell.

3. Device according to claim **1**, wherein each winding of the second cell is inferred from the corresponding winding of the first cell by means of axial symmetry along an axis which is co-linear with the joined faces.

4. Device according to claim **1**, wherein each cell comprises at least one first and one second winding wound in opposite directions around the same bar.

5. Device according to claim **1**, wherein each cell comprises at least one first and one second winding, the first winding and the second winding being connected to respective phases of the power source in such a way that, during operation, the angular phase difference between the supply voltages of each of said windings is between

$$\pi - \frac{2\pi}{N} \text{ and } \pi + \frac{2\pi}{N}.$$

6. Device for powering an electric dipole, comprising:

a power source with N phases, the angular offsets between the phases being distributed uniformly between 0 and 2π rad, N being greater than or equal to four and 2π rad representing a period of the voltage or the periodic current,

a multi-interphase transformer which can be broken down into at least four elementary magnetic cells, each cell comprising:

a magnetic core suitable for forming only a first and a second closed annular magnetic circuit with a common portion, said core comprising a central magnetic bar forming the common portion of the two closed magnetic circuits, and at least two non-colinear bars each having a planar face facing towards the exterior of the cell, and the field lines of the first or second closed magnetic circuit inside said bars being parallel to the planar face thereof,

one or more windings, each of said windings being wound around the central bar so as to leave at least the two bars with a planar face free of windings, and

the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another,

in which:

a) the or each winding of the first cell is connected to a respective phase of the power source so as to produce, during operation, a magnetizing flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) the or each winding of the second cell is connected to a respective phase of the power source so as to produce, during operation, a magnetizing flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j,

characterized in that the absolute value of the difference between the angular offsets x_i and x_j is greater than

$$\frac{4\pi}{N} \text{ rad.}$$

7. Device according to claim **6**, wherein the absolute value of the difference between the angular offsets x_i and x_j is between

$$\pi - \frac{2\pi}{N} \text{ rad and } \pi + \frac{2\pi}{N} \text{ rad}$$

for each cell.

8. Device according to claim **6**, wherein each winding of the second cell is inferred from the corresponding winding of the first cell by means of axial symmetry along an axis which is co-linear with the joined faces.

9. Device according to claim **6**, wherein each cell comprises at least one first and one second winding wound in opposite directions around the same bar.

10. Device according to claim **6**, wherein each cell comprises at least one first and one second winding (e_{1i}, e_{21}), the first winding and the second winding being connected to respective phases of the power source in such a way that, during operation, the angular phase difference between the supply voltages of each of said windings is between

$$\pi - \frac{2\pi}{N} \text{ and } \pi + \frac{2\pi}{N}.$$

11. Method of powering a multi-interphase transformer which can be broken down into at least four elementary magnetic cells, each cell comprising:

a magnetic core suitable for forming a single closed annular magnetic circuit, said core comprising for this purpose at least three non-co-linear bars forming the closed magnetic circuit, at least two of said bars each having a planar face facing the exterior of the cell, and the field lines of the closed magnetic circuit inside said bars being parallel to the planar faces,

one or more windings, each of said windings being wound around a bar of the magnetic core so as to leave at least the two bars with a planar face free of windings, and

the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another,

this method consisting of powering said multi-interphase transformer by using N periodic supply voltages or currents which are offset angularly from one another, the angular offsets between the N supply voltages or currents used being distributed uniformly between 0 and 2π rad, N being an integer greater than or equal to four and 2π rad representing a period of the voltage or the periodic current, and more specifically consisting of:

a) powering the or each winding of the first cell with one of the supply voltages or currents respectively so as to produce a magnetizing flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) powering the or each winding of the second cell with one of the supply voltages or currents respectively so as to produce a magnetizing flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j,

characterised in that the absolute value of the difference between the angular offsets x_i and x_j is greater than or equal to

$$\frac{4\pi}{N} \text{ rad.}$$

12. Method according to claim **11**, wherein the absolute value of the difference between the angular offsets x_i and x_j is between

$$\pi - \frac{2\pi}{N} \text{ rad and } \pi + \frac{2\pi}{N} \text{ rad}$$

for each pair of cells.

13. Method according to claim **11**, wherein each winding of a cell is connected in series with at least one other winding of another cell.

14. Method of powering a multi-interphase transformer which can be broken down into at least four elementary magnetic cells, each cell comprising:

a magnetic core suitable for forming only a first and a second closed annular magnetic circuit with a common portion, said core comprising a central magnetic bar forming the common portion of the two closed magnetic circuits, and at least two non-co-linear bars each having a planar face facing towards the exterior of the cell, and the field lines of the first or second closed magnetic circuit inside said bars being parallel to the planar face thereof,

one or more windings, each of said windings being wound around the central bar so as to leave at least the two bars with a planar face free of windings, and

the elementary cells are joined together in pairs via the respective planar faces thereof so as to form pairs of first and second cells which are magnetically coupled to one another,

the method consisting of powering said multi-interphase transformer by using N periodic supply voltages or currents which are offset angularly from one another, the angular offsets between the N supply voltages or currents used being distributed uniformly between 0 and 2π rad, N being an integer greater than or equal to four and 2π rad representing a period of the voltage or the periodic current, and more specifically consisting of:

a) powering the or each winding of each first cell with one of the supply voltages or currents respectively so as to produce a magnetizing flux in the bar of the first cell joined to the second cell, the fundamental component of which has an angular offset x_i, and

b) powering the or each winding of the second cell with one of the supply voltages or currents respectively so as to produce a magnetizing flux in the bar of the second cell joined to the first cell, the fundamental component of which has an angular offset x_j,

characterized in that the absolute value of the difference between the angular offsets x_i and x_j is greater than

$$\frac{4\pi}{N} \text{ rad.}$$

15. Method according to claim **14**, wherein the absolute value of the difference between the angular offsets x_i and x_j is between

$$\pi - \frac{2\pi}{N} \text{ rad and } \pi + \frac{2\pi}{N} \text{ rad}$$

for each pair of cells.

16. Method according to claim **14**, wherein each winding of a cell is connected in series with at least one other winding of another cell.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 8,009,003 B2
APPLICATION NO. : 12/446035
DATED : August 30, 2011
INVENTOR(S) : Laboure et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the title page, please amend Item (73) to read as follows:

-- (73) Assignees: **Centre National de la Recherche Scientifique (C. N.R.S.)**, Paris, (FR); **Institut National Polytechnique de Toulouse**, Toulouse, France; **Universite Montpellier 2, Sciences et Techniques**, Montpellier, France --

Signed and Sealed this
Sixth Day of December, 2011

David J. Kappos
Director of the United States Patent and Trademark Office